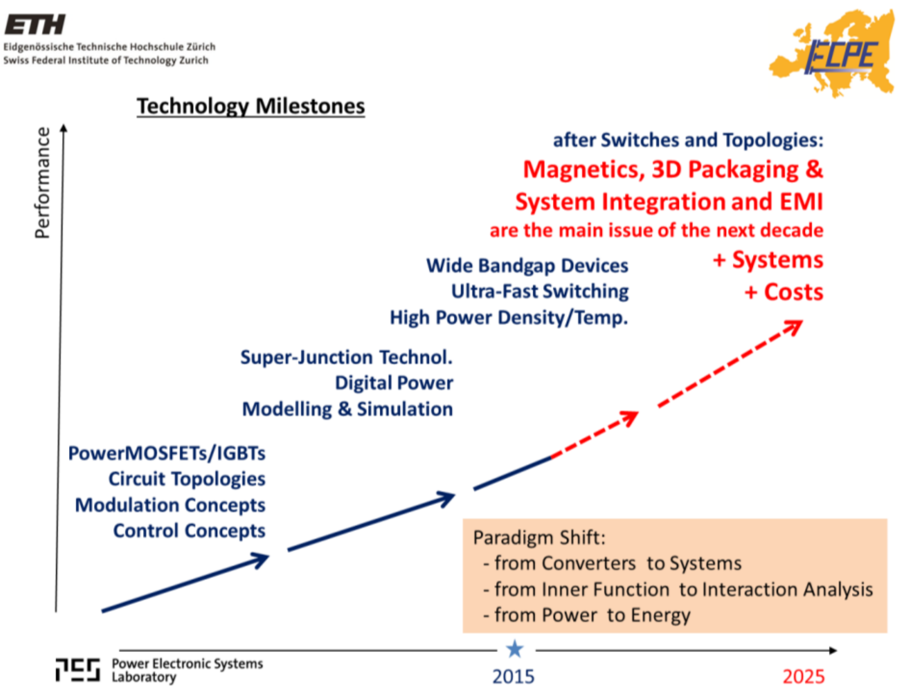
ECPE Position Paper

on

Next Generation Power Electronics based on Wide Bandgap Devices

- Challenges and Opportunities for Europe



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The ECPE Position Paper is dedicated to the memory
of José Millán who passed away on 3rd May 2016.

1. Introduction

1.1 Power Electronics Today

Today already 40% of the world wide used energy is provided by electric power. It is expected that this share is going to rise to about 60% until 2040. This enormous amount of energy not only needs to be produced environmentally friendly, but it also should be distributed and used efficiently. Power Electronics is the technology associated with the efficient conversion, control and conditioning of electric energy from the source to the load. It is the enabling technology for the generation, distribution and efficient use of electrical energy. It is a cross-functional technology covering the very high Giga Watt (GW) power (e.g. in energy transmission lines) down to the very low milli Watt (mW) power needed to operate a mobile phone. Many market segments such as domestic and office appliances, computer and communication, ventilation, air conditioning and lighting, factory automation and drives, traction, automotive and renewable energy, benefit from the application of power electronics technology.

Power Electronics is key for improving energy efficiency and enabling a sustainable energy supply based on renewables. As a cross-functional technology it is enabling

- efficiently feeding-in wind and solar energy to the grids,
- stabilising the power grids with increasing share of fluctuating renewable energies,
- highly efficient variable speed motor drives,
- energy efficient and low-emission mobility with hybrid and full electric vehicles,
- an energy saving lighting technology,
- efficient recovery of braking energy,
- energy management of batteries,
- control appliances and building management systems via the grid interface (smart grids)

Key statements:

- ➢ *The power semiconductor device is the key driver and enabler in power electronics systems.*
- ➢ *Today power electronics is dominated by the power semiconductor material silicon. A very mature technology has been developed over decades with cost efficient high volume production up to 300 mm wafer technology.*
- ➢ *Different Si-based power devices are available for a wide power range from a few hundreds of Volts (and below) to several kV and from mA to kA for different target applications e.g. for switched mode power supplies, motor control and energy transmission and distribution.*
- ➢ *For the economic impact the leverage effect from the power semiconductor to the system level has to be considered with a typical factor of 100, see figure 1.*
- ➢ *After decades of silicon carbide materials and device research a variety of SiC devices are available on the market.*
- ➢ *With gallium nitride another wide bandgap (WBG) material has been proposed for power electronics based on the experience in optoelectronics and microwave electronics. Besides the traditional bulk GaN technology using expensive 2-inch GaN wafers, an alternative approach of GaN-on-SiC and especially GaN-on-Si epitaxial wafers is pursued for power applications.*

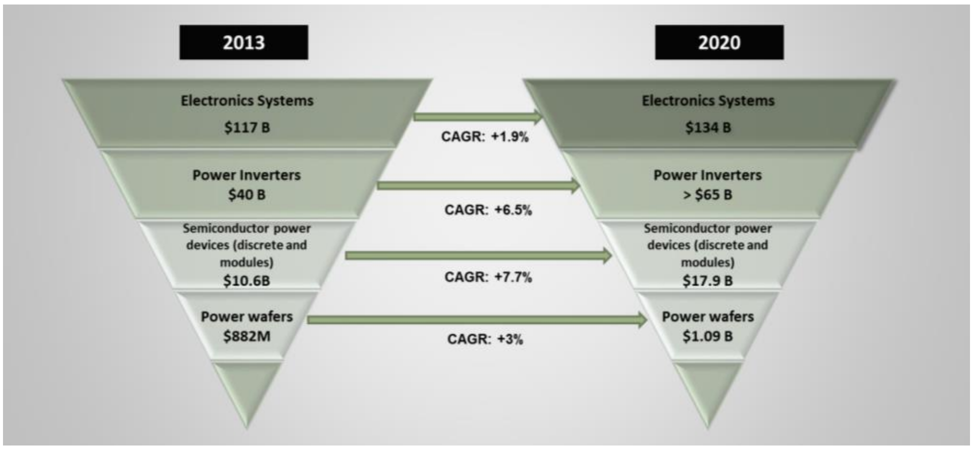

Fig. 1 Power Electronics value chain: wafer, device, converter, system (Yole Dév., [5])

1.2 Wide Bandgap (WBG) Materials and Devices

As stated before, the current Power Semiconductor market is dominated by silicon technology. The performance of this technology has been improving steadily as the technology has matured over the past 30 years, but has now reached the stage where its fundamental material properties limit the capability and efficiency of power semiconductor systems.

GaN and, especially, SiC process technologies are by far the most mature among WBG semiconductor materials, and therefore, more attractive from the device manufacturer's perspective for high power electronics. Although GaN theoretically offers better high frequency and high voltage performances over the whole range of applications, the lack of good quality bulk substrates required for vertical devices and the lower thermal conductivity lend SiC the better position for high-voltage high-power devices with classical Si like structures (PowerMOSFETs, IGBTs, GTOs). On the other hand, the industrial interest for GaN power devices is increasing steadily. In the last decade, GaN technology has been maturing fast, primarily due to light-emitting diodes (LEDs) manufacturing, but now also as a platform for high frequency, high voltage electronics, especially focused on GaN-based hetero-junction high electron mobility transistors (HEMTs).

The superior material properties of SiC have been recognised as the way forward and many announcements of breakthroughs were made in the past. Due to the commercial availability of the starting material (6 inch wafers, 8 inch wafer diameter has been demonstrated), and a relative maturity of the technological processes, the SiC diode technology for example is already successfully competing with Si power diodes in the semiconductor market, in particular for lower power applications up to 1200-1700V. However, the SiC transistors available today still have high production costs and perform poorly compared to their potential. In any case, when compared to other WBG materials, SiC currently offers advantages for the HV range (≥ 1200V). The SiC technology, pretty compatible with the Si one, allows building equivalent power device structures developed for Si both in unipolar and bipolar conduction configurations.

The great advantage of GaN technology is definitively the possibility to build efficient hetero-junctions, opening the way to a large number of novel power devices structures (hetero-junctions in SiC remain unsuccessful and do not look promising). A two-dimensional electron gas (2DEG) is formed in AlGaN/GaN heterostructures due to the large conduction band discontinuity between GaN and AlGaN and the presence of polarization fields allowing a large 2DEG concentration with high electron mobility values (1200-2000cm^2/Vs). GaN-on-Si or GaN-on-SiC lateral HEMTs are currently developed for the 200V-1200V range. Due to its lateral structure, limited reliability and lack of robust avalanche and thermal resistance, such lateral devices will be limited to the low voltage and medium power range of applications. They are not suited for high voltage (>1200V) power systems.

Another interesting WBG semiconductor for power applications is diamond. From the theoretical point of view, diamond is very attractive for high voltage devices but a lot of technological breakthroughs need to be achieved before devices will become commercially available. For instance, substrates are limited to not more than 7mm×7mm today. Moreover, diamond devices will be limited to p-type unipolar operation due to the extreme difficulty to dope n-type. And even the p-type doping requires a high activation energy, such that at room temperature only a very small fraction of the dopants is active ("incomplete ionisation") and the conductivity is by orders of magnitude inferior compared to its theoretical value. All these limitations make diamond a much longer term WBG material for industrial use in high power electronics than SiC. Quite similar comments can be made for aluminium nitride (AlN) and gallium oxide (Ga_2O_3) which are also highly resistive at room temperature. However, Ga_2O_3 promises melt-growth production of single crystals and, thus, a massive cost advantage over other WBG materials. So far 2 inch wafers have been demonstrated but the material quality is still questionable and significantly more work on the material is required before devices suited for power electronics will be available.

SiC Material

State-of-the-art: For the material part, there are two main limiting issues for any semiconductor to become the dominating material for the next generation of power electronics: cost and quality. SiC requires much higher growth temperatures and has growth rates about 100 times slower than Si. This gives more complex growth equipment and longer growth times, which increase the production cost. The material quality has improved drastically in the last decades, with both increased wafer diameters and reduced defect density. For HV and large area devices the main issues are currently the epitaxial defects, the carrier lifetimes and the basal plane dislocation (BPD) densities. The epitaxial defects are today in the order of 1-2cm^{-2} and limit the yield for large area devices. For bipolar devices, BPDs are critical defects, since they replicate from the substrate into the epitaxial layer due to the off-axis cut substrates. During bipolar operation the BPDs expand to form stacking faults which degrades the device performance. Many attempts with different buffer layers to reduce the BPD density in the epitaxial layer have been reported, and the best material today has a BPD density of about 0.1cm^{-2}. In addition, one of the most important material properties especially for UHV devices is the minority carrier lifetime. The minority carrier lifetime in as-grown epitaxial material is in the order of 1-2µs, and in as-grown HTCVD material below 10ns, while UHV devices require lifetimes up to or above 10µs. Therefore, a great R+D effort has to be done in this field. However, the current methods used to reduce BPDs and to increase lifetime are time and process costly.

Beyond the State-of-the-art: A typical HV SiC power device is fabricated from a highly doped substrate grown by PVT, with an additional thick, low doped epitaxial layer for HV blocking (approx. 10µm per 1kV blocking). To reduce cost and increase quality, the goal is a SiC substrate with high purity and a low doping level (~10^{14}cm^{-3}) to be used for direct device processing of UHV blocking devices without the need for epitaxy. The HTCVD process could provide a material with very low concentration of extrinsic defects, allowing growing the material on on-axis seed crystals to eliminate the problem with BPDs penetrating along the standard off-axis substrates, which causes the so called bipolar degradation. Besides, wafer thinning and polishing processes could be performed to obtain wafers with a thickness of 30-200µm, and to reduce as much as possible the remaining intrinsic defects and dislocations, as well as series resistance. The use of HTCVD substrates as active layer followed by implantation regions on top and back, for carrier injection, could bring an economical and an industrially viable process to produce material for HV devices.
A complement to the high purity HTCVD substrates is the development of a process for conventional epitaxial growth with high growth rate, for growing 30µm to 200µm thick layers. The epitaxial process should provide a defect density below 0.2cm^{-2}. An optimisation of the buffer layer between substrate and epitaxial layer will be needed for reducing the density of critical BPDs (<0.1cm^{-2}).

SiC Devices

State-of-the-art: Concerning SiC rectifiers, SiC SBDs have been commercially available since 2001. They currently range from 600V/20A and 1.2-1.7kV (3.3kV very recently), with current capabilities as high as 50A. With respect to SiC switches, 1200V SiC MOSFETs have been commercially available since 2011. Normally-off SiC JFETs, with vertical channel and no body diode, are also commercially available (10 to 20A @ 1200V per chip). Normally-on 1200V SiC JFETs, with lateral channel and body diode, are also in the market. SiC 1200V, 12A and 40A BJTs are also commercially available and SiC 6500V thyristors have been announced recently. In addition to commercial devices, almost all Si power device structures have been demonstrated also in SiC, with a special recent emphasis in IGBTs.

Beyond the state-of-the-art: Today most of commercial SiC devices have relatively low voltage values (≤ 1.7kV). The current rating of commercial devices is also remarkably lower compared to Si high power IGBTs, which is linked to the fact that there are still many issues associated with the material quality and the process technology to be solved. However, there is a strong interest in exploiting the SiC HV and UHV capabilities, and several achievements at lab level have been reported (from USA and Japan), such as 26kV PiN diodes, 10kV MOSFETs, and > 20kV n and p-channel IGBTs, among others.
Development of advanced cost-efficient power systems based on HV and UHV devices is globally considered a key technological enhancement necessary for enabling transmission and distribution of electricity from both dispersed and concentrated renewable sources. From this perspective, the development of advanced SiC material with high lifetime and the design and fabrication devices from 3.3kV to 20kV operating with high current density based on these superior SiC material is a key enabler for development of energy efficient power electronic systems of the future. The foreseen chip size will be at least $1cm^2$ in accordance with the starting material expectations. Although it is difficult to predict precisely the current levels since they highly depend on the lifetime control, it is expected that a 20kV SiC device could handle currents by far exceeding 100A for $1cm^2$ chip size *[T. Kimoto. "Ultrahigh voltage devices for future power infrastructure". www.compoundsemiconductors.net, March 2014].*

GaN Material

The main approach today with GaN power devices technology is to build hetero-junction lateral or quasi-vertical devices. For this purpose, and due to the lack of GaN bulk substrate, GaN, AlGaN, InAlN epilayers stacks have been mainly grown on foreign substrates, particularly, SiC, Sapphire and Si. Growing high-quality, single-crystalline GaN films, which are essential for the power conversion, require a well-defined global epitaxial relationship between the epitaxial GaN film and the substrate. Among the diverse possibilities, GaN epilayers grown on Si substrates offer a lower cost technology compared to the other substrates as well as allowing material growth on large diameter substrates up to 200mm.

Two inches GaN substrates can be grown with different methods such as high temperature HVPE (Hydride Vapour Phase Epitaxy), but the cost is very high and the substrate quality is by far inferior to that of SiC. In addition, the gain in performance of homo-epitaxial GaN unipolar power devices versus SiC equivalents is low and does not justify the higher cost of GaN substrates. Then, the development of GaN substrate growth production technology is not justified today and in the near future.

GaN Devices

State-of-the-art: Most of GaN Schottky power diodes reported up to now are either lateral or quasi-vertical structures. Breakdown voltages of lateral GaN rectifiers as high as 9.7kV have been obtained on sapphire substrates, although the forward voltage drop is still high. GaN rectifiers implemented on silicon or sapphire substrates are attracting a lot of attention because of their lower cost. However, their performance does not overcome the SiC ones due to a larger device area needed for a given nominal current. Moreover, issues with UIS (Unclamped Inductive Switching) and avalanche capability restrict these lateral GaN rectifiers´ applications. Recently, with the availability of free-standing GaN substrates, 600-1200V GaN Schottky diodes are due to be launched in the market to compete with SiC Schottky rectifiers. On the other hand, JBS GaN diodes are also being investigated, which could further increase the performance of GaN-based power rectifiers in the 600V to 3.3kV range, although improvements in the contact resistance to implanted p-type GaN are still needed.

State-of-the-art HEMTs: AlGaN/GaN high electron mobility transistors (HEMTs) are intrinsically normally-on devices since a negative bias must be applied to the gate for removing the 2DEG. These devices have attracted a great attention in recent years with a remarkable trade-off between specific on-resistance and breakdown voltage. They are well suited for high power switching applications, with a projected ×100 performance advantage in the square breakdown voltage per specific on-resistance figure of merit (V_{BR}^2/R_{ON}) over silicon power devices. These devices are very attractive for switching power supplies with ultra-high frequency (in the MHz range) and as microwave power devices for base station of cellular phone. Remarkable improvements have been made since the appearance of the first GaN based HEMT switch. For instance, the output power capability at microwave frequencies of GaN based HEMTs on both Sapphire and SiC substrates has improved from initial 1.1W/mm in 1996 up to 40W/mm. Extremely high voltage HEMTs (8.3kV) with a low specific on-state resistance value of 186mΩ·cm^2 have been demonstrated on a Sapphire substrate with an improved heat dissipation performance by using via-holes through the Sapphire at the drain electrodes. However, today, the main industrial developments of GaN HEMT are toward GaN on Si substrate, to reduce costs and be competitive with silicon and SiC in the <1.2kV range.

One of the main issues in improving the electrical performance of the first HEMT structures was to suppress the drain current collapse and to increase the gate to drain breakdown voltage by controlling the bulk and surface trap densities. In this sense, several approaches have been proposed including the surface-charge-controlled n-GaN-cap structure, the recessed gate and field-modulating plate structure, and the passivation of surface states via silicon nitride or other dielectric layers.

GaN HEMTs are basically normally-on devices, which makes it difficult to use them in power systems where normally-off switches are preferred for safety and ease of use reasons. Thus, a research effort was spent in recent years to develop normally-off GaN HEMT structures through several approaches such as the use of a recessed-gate structure, fluorine-based plasma treatment of the gate, combination of the gate recess together with a fluorine-based surface treatment or the selective growth of a pn junction gate. The current tendency is to associate a HEMT with a MOS recess gate. However, all these techniques degrade the forward conduction capability compared to an equivalent normally-on transistor. Normally-on and off GaN HEMTs are commercially available with a breakdown voltage in the 20V-600V range. As examples, EPC supplies normally-off GaN HEMTs from 40V/33A to 200V/12A.

Beyond state-of-the-art: The following topics should be addressed:

Eliminate current collapse and to control the charge trapping since it is highly related to the dynamic R_{ds_on}. The increase of the blocking capability range is also foreseen. Concerning GaN HEMTs on Si, a significant achievement was the silicon removal approach accounting for a significant power increase of these HEMT structures. Specifically, a 2.2kV HEMT fabricated on Si using a new local Si substrate removal technology has been reported, which represents a significant improvement in comparison with HEMT reference structure on bulk Si showing a blocking voltage capability of 700V. In this sense, devices with avalanche capability should be envisaged. Currently a breakdown voltage V_{br}>750V allows 600V operation with reasonable margin.

Improvement of normally-off HEMTs with positive threshold voltage (V_{th} > 1.5-2V) and increased current capability (I_{ds_max} > 50 A) should be another goal.

Vertical devices will only represent a real breakthrough if they combine vertical conduction with hetero-junction channels.

New structures such as advanced GaN based bidirectional Super Heterojunction Field Effect Transistor (BiSHFET) using the polarisation junction concept have been recently proposed. The fabricated HEMTs with Schottky and PN junction gate structures are arrayed on an insulator substrate of Sapphire and the measured isolation voltage between the devices is more than 2kV with measured on-resistances of 24Ω·mm and 22Ω·mm in both directions, respectively, ref. (6). It is also worth to remark that advances in GaN HEMT process technology enable the integration of GaN diodes, which can be used to protect the HEMTs' gate against voltage peaks. Furthermore, GaN smart power technologies are also under development allowing the monolithic integration of high voltage power devices and low-voltage peripheral structures for sensing/protection/control purposes.

Finally, the use of other top layers in GaN HEMTs would be an alternative to AlGaN, such as InAlN to improve the HEMT performance.

As in the case of SiC devices, advanced packages should be developed to get full performance of the WBG semiconductors in switching frequency, high temperature and high voltage operations.

The commercial status of the GaN-on-silicon power industry is described in reference (7).

1.3 Next Generation Power Electronics

The Wide Bandgap (WBG) semiconductors silicon carbide (SiC) and gallium nitride (GaN) offering higher efficiency and higher power density compete against the dominating power semiconductor material silicon.
The advantages of WBG semiconductors on system level, higher voltage and temperature operation as well as higher switching frequency enabling volume and weight reduction, are related to fundamental material properties of these materials, e.g. electric field, energy gap, electron velocity, melting point and thermal conductivity, see figure 2.
Fast switching will become key in many applications because this will open a new generation of power electronics. Increasing the switching frequency enables the miniaturisation of passive components for energy storage and filtering in power electronic systems. In a photovoltaic inverter, for example, the increase of switching frequency from 48 kHz to 250 kHz results in a weight and volume reduction by a factor of five.

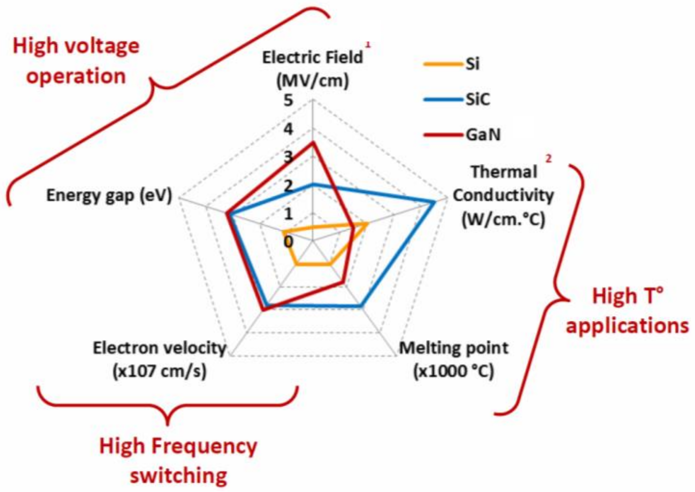

Fig. 2 Key characteristics of GaN vs. SiC vs. Si

Therefore, we will enter a next generation of power electronics based on wide bandgap power semiconductors where it will be possible to fully exploit the potential of the new semiconductor devices on systems level, see figure 3.

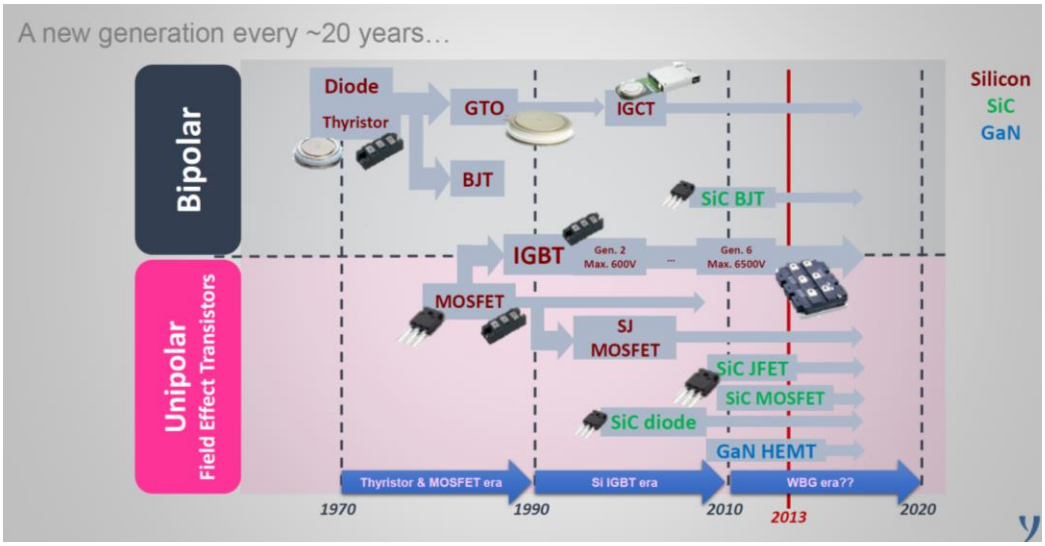

Fig. 3 Life cycle of power device technologies (Yole Dév., [5])

2. Role and Importance of Power Electronics

2.1 Power Electr. as Key Enabler e.g. for Energy Efficiency, Renewable Energies & Smart Grids

Role of power electronics in improving energy efficiency

Power Electronics is the technology associated with the efficient conversion, control and conditioning of electric energy from the source to the load. It is the enabling technology for the generation, distribution and efficient use of electrical energy. The following large electrical energy consuming sectors demonstrate the significant energy-savings potential related to power electronics.

- **Motor control** including industrial applications, home appliances, ventilation and air conditioning, lifts and traction drives
  It is estimated that motor-driven systems account for more than 50% of total electricity consumption (65% of industrial electricity, 38% of tertiary and 35% of residential). The energy-saving potential of Variable Speed Drives (VSDs) originates from the ability to control the motor speed to match the output with the system needs at very high efficiencies. The energy savings potential by introducing VSDs is estimated to be 30 - 40% for most applications. The technical potential for energy savings is relevant for about 40 - 50% of all motors depending on the application, and given that VSDs have already been applied to about 15 - 20% of all motors the remaining potential is estimated to be about 30%. There is an additional energy saving of 20 % through the recuperation of electrical machines during the slow down process of the speed which is frequently used in elevators and traction application of trains and heavy vehicles with power electronic converters. Combining all these figures, the total electrical energy-savings potential of VSDs is about 5 - 6% of the current electrical energy consumption.

- **Lighting** in commercial, industrial and residential building, and street lighting
  The savings are related to new technologies based on solid-state lighting (LED) requiring electronic power conversion. By operating LEDs with pure digital controlled power converters the lifetime is significantly longer along with an additional energy saving potential.

- **Information and Communication Technology (ICT)**
  Electrical energy demanded by *data centers and servers* in Western Europe was 56 TWh in 2007 and is forecast to increase incrementally to 104 TWh in 2020. In a typical data center, less than half of this power is delivered to the compute load, which includes microprocessors, memory and disk drives. The rest of the power is lost in power conversion, distribution, and cooling. The use of advanced power electronics techniques, like new DC distribution networks, can lead to a 10% reduction of the required energy. The integration of ICT technologies and power electronics and improving energy management can save an additional 20%. Further research on reliability, implementation and cost reduction can further improve these numbers.
  Estimates indicate that the telecom industry consumes 1% of the global electricity, and more than 90% is consumed by network operators. Almost 30% of electrical energy savings can be achieved in *radio base stations* (RBS) by employing efficient power electronics technologies such as efficient power amplifiers and techniques for low consumption in standby mode. In ICT applications power supplies require ultra-high power density along with high efficiency at the same time. With the new power devices and optimised passive components this target can be achieved.
  The annual electricity consumption related to standby functionalities and off-mode losses in the EU was estimated to have been 47 TWh in 2005. It has been estimated that the total annual energy savings potential for standby consumption in the EU is 35TWh, and power semiconductor manufacturers claim that more than 90% standby consumption reduction is feasible.

Role of power electronics for e-mobility

The mobility and transport sector is the fastest-growing sector in the European economy and, being responsible for above 30% of total primary energy consumption, represents the largest primary energy consumer in the EU. Final energy consumption in the transport sector grew 28.6% in the EU-25 between 1990 and 2004. Increasing fuel prices and the global energy situation have triggered worldwide investment in electric and hybrid vehicles and increasing penetration of these vehicles into the market. Power electronics is an enabling technology for the development of drive trains and battery-charging for these cleaner and more fuel-efficient vehicles. Furthermore, the increasing electrification of previously mechanical and hydraulic vehicle functions, such as x-by-wire applications like electric power steering or electric braking are only possible through the use of power electronics.

Hybrid electric buses using hybrid electric vehicle propulsion technology are increasingly becoming part of public transport in cities around the world. They offer considerable fuel savings and reduce emissions. Power electronics is a necessary part of the drive train of these buses.

Aviation is responsible for ~12% of the transport energy consumption and is the fastest-growing energy consumer in the EU, with an increase of 73% between 1990 and 2006. Air transport demand is predicted to double in the next 10 - 15 years and triple in 20 years. More electric aircrafts where bleed air and hydraulic power sources are replaced with electrical equivalents, thus enabling a significant improvement in efficiency, system flexibility, aircraft reliability and specific fuel consumption, also depend on power electronics as an enabling technology. Boeing’s More-Electric-Aircraft 787 Dreamliner has achieved a 20% reduction in fuel and CO_2 compared to its conventional counterpart 767 primarily due to its efficient no-bleed engines and the composite airframe. Power electronics systems are crucial for the aircraft’s distributed power system and the total power electronic load is 1MW compared to several kW in conventional aircrafts.

Role of power electronics for integration of renewables and the Smart Grid

The increasing energy demand, the shortage and finiteness of fossil fuels and the need for carbon footprint reduction in order to prevent hazardous climate changes have brought the issue of energy into the spotlight of political and public attention. Electrical energy is one of the cleanest, most efficient and versatile forms of energy and it is predicted that its demand will continue to grow at a much faster rate than other energy sources in the coming decades. In recent years there has been a growing awareness within the electricity supply industry of the need to reinvent Europe’s electricity networks in order to meet the demands of twenty-first-century customers. In 2005 the European Smart Grids Technology Platform was established as a coherent approach to meet the challenges envisaged by network owners, operators and particularly users, across the EU. In the EC paper “Vision and Strategy for Europe’s Electricity Networks” it was concluded that future electricity markets and networks must provide all consumers with a highly reliable, flexible, accessible and cost-effective power supply, fully exploiting the use of both large centralised generators and smaller distributed power sources across Europe. End users will become significantly more interactive with both markets and grids; electricity will be generated by centralised and dispersed sources; and grid systems will become more inter-operable at a European level to enhance security and cost-effectiveness. This new concept of electricity networks is described as the ‘Smart Grids’ vision.

One of the priority actions of the EC Action Plan for Energy Efficiency is to make power generation and distribution more efficient. Transmission and distribution (T&D) losses of electrical energy are typically between 6% and 8%. A European Task Force T&D Working Group has identified a number of energy-efficient technologies for grids, including power electronics technologies such as HVDC, FACTS, power electronic transformers, distributed generation and microgrids. Power electronics is necessary to interface distributed generators such as wind turbines and solar cells to the grid.

Power electronics has been identified as a key technology in all four pillars of Smart Grids:

- **Integration of renewables:** wind turbine converters, HVDC for offshore wind park connection, SVC/STATCOM for grid code compliance, energy storage for improving stability and decreasing power fluctuations, solar inverters,
- **Integration of electric vehicles:** (fast) charging of electric vehicles, traction drive for hybrid electric vehicles, dynamic energy storage to absorb peaks due to simultaneous charging of electric vehicles,

- **Reliability and efficiency:** efficient long distance transmission with HVDC, variable speed drives in industrial plants and pumped hydro stations, energy storage for emergency and peak power, power quality solutions for industry,
- **Demand response:** converter interface to distributed generation with built-in load management capability drives in pumped hydro station with remote control from control centre.

Role of power electronics in industrial manufacturing incl. Industry 4.0

Nearly one-third of the world's energy consumption and 36% of its carbon dioxide (CO_2) emissions are attributable to manufacturing industries. Manufacturing is still the driving force of the European economy, contributing over 6.500 billion euro in GDP. It covers more than 25 different industrial sectors, largely dominated by SMEs. There is an increasing demand for greener, more customised and higher quality products. The European manufacturing sector faces an intense and growing competitive pressure in global markets. European companies are faced with continuous competition in the high-tech sectors from other developed economies, such as the U.S, Japan and Korea. Manufacturing has to address the challenge of producing more products with less material, less energy and less waste. Together with other industrial technologies, ICT and advanced materials, power electronics-enabled variable-speed control of motors as an enabler for higher automation and better process control will improve the competitiveness of the companies. Power electronics in combination with wireless sensor technology can also be utilised for machine conditional monitoring applications, checking that electrical machines are operating in accordance with expected efficiency standards as well as enabling predictive maintenance to ensure machines are repaired/maintained in advance of breakdown thereby minimising downtime and associated losses.

Key statements:

- *Power electronics is a key technology for the efficient conversion, control and conditioning of electric energy from the source to the load.*
- *The energy saving potential of power electronics in various applications is related to highly efficient variable speed motor drives with energy recovery, to smart power supplies enabling high efficiency over a wide load range and zero-power standby function as well as to energy efficient and low-emission mobility with hybrid and full electric vehicles.*
- *Furthermore, power electronics is enabling a sustainable energy supply based on renewables by feeding-in wind and solar power efficiently to the electricity grid and by stabilising the grids while the share of fluctuating renewables is increasing.*
- *The estimated energy savings potential that can be achieved by introducing power electronics into systems is enormous, more than 25% of the current EU-25 electricity consumption.*

2.2 New Opportunities Related to Wide Bandgap Power Electronics

Wide band gap power semiconductors are expected to serve as enabling elements in disruptive solutions in nearly all areas mentioned in the chapters before. Nearly loss-less switching and an outstanding partial load efficiency of potential switch technologies are the key value propositions of those new components. Emerging markets are of special interest for new technologies in general due to the naturally lower adaption hurdle and the market pull impact expected from a successful implementation. Examples are here mainly the area of battery management in the modern smart grids being highly influenced by renewable energy sources as well as the whole infrastructure for charging electric cars and buses. The knowledge base in Europe in this area combined with the technological leadership in power semiconductors and wide band gap in particular are ideal prerequisites for generating a leading position of European products for those new application segments. In existing application segments innovative circuit solutions are enabled opening up new horizons in efficiency and power density. WBG transistors are key elements for server power supplies entering the 99% A-Z efficiency area. Corresponding power modules could for instance serve to upgrade existing non-VSD motors in an easy way towards much more efficient speed controlled systems without significant changes in the infrastructure by the ability to offer inverters, which can be mounted directly on the motor.

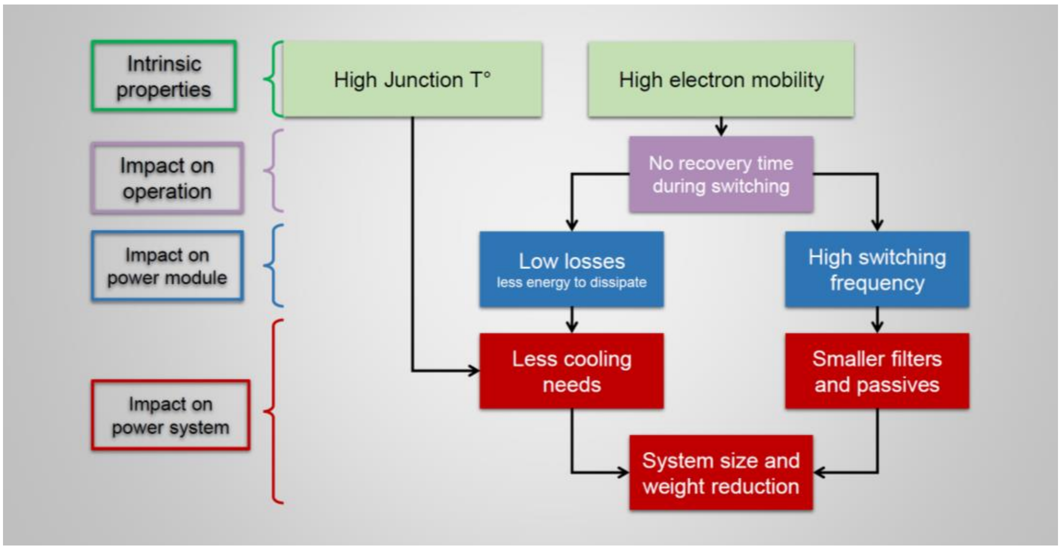

Fig. 4 Reasons for WBG added value and related impact (Yole Dév., [5])

Key statements:

- *Wide bandgap power electronics is an emerging market segment on the device level as well as on the systems level.*
- *We will see disruptive system solutions with ultra-compact and integrated converters.*
- *Europe has a good starting position for technology leadership in wide bandgap power electronics.*

2.3 Benefits of Wide Bandgap Technology on System Level

Applying WBG semiconductors in power electronic systems, it is not sufficient to just replace the Si devices by SiC or GaN. This approach will lead to minor advantages only, which will not justify the higher device costs. To fully exploit the advantages of WBG power semiconductors on system level, mainly higher efficiency and higher power density, a system approach is necessary. To leverage the full potential of WBG based power semiconductors in the majority of applications a system re-thinking is required. This situation is also the reason for the expected higher adaption rate in emerging applications where this mental hurdle is not in place. Major aspects are new limits in switching speed, which require highly skilled system design competencies in order to manage parasitic effects and to comply with EMI requirements. The shrink potential offered by WBG elements is a chance and challenge as well since the much lower absolute losses are now concentrated in a much smaller volume/area and, thus, the actual power density is increasing despite the significant reduction of total losses. This requires more sophisticated cooling solutions in the application. Furthermore, the interface between the semiconductor and the circuits needs a completely new philosophy, starting with new housing concepts for the semiconductors and being extended towards the geometry of passive components needed for the full system. In general, the availability of suitable peripheral elements like capacitors, inductors, drives and microcontrollers is a key for a successful roll out of the new technology. As an example, high power inductive components can be mentioned – today those are not available for the frequency range above 100kHz which could be entered by using WBG power switches in high power and high voltage. The European industrial and academic landscape is able to offer both, the know-how and manufacturing capability to provide a complete set of components for leveraging the full potential of WBG and to manifest a technological leadership position.

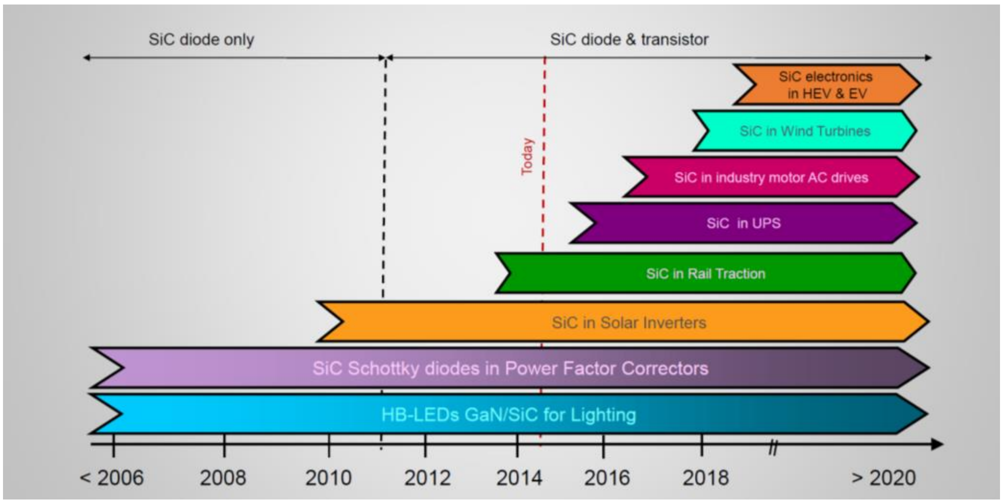

Fig. 5 SiC device application roadmap (Yole Dév., [5])

<u>*Key statements:*</u>

- *The system level benefits that could be achieved with next generation power electronics are related to improved efficiency, reduced volume and weight, higher level of integration, possible savings at cooling costs and passive components and better functionality.*
- *Just replacing Si dies by WBG dies in conventional modules and assemblies will not allow to fully exploit the benefits and potential of WBG semiconductors. The minor improvements, which can be achieved in this approach will not justify the higher chip costs.*
- *The full benefits of WBG devices including cost advantages can only be realised on system level in those applications, which pay for the improvements in efficiency or power density.*

3. Status of Today and Technology Gaps

<u>3.1 SWOT Analysis for Power Electronics in Europe</u>

Since power electronics is a key technology in achieving a sustainable energy society, the demand for power electronics solutions will show significant growth in the coming decades. The European industry holds a strong position in the field of power semiconductors and modules and is establishing a WBG semiconductors technology base. Europe also has high quality power electronics research groups at universities and research institutes with well-established networks and associations in Europe to provide platforms for discussion, cooperation and joint research. On the other hand, outsourcing of research and technology to other countries (not only Japan, USA, but also emerging countries), strong research increment in these countries, and the possibility of key European companies being taken over by competitors from Asia, makes it even more critical for Europe to keep up with the technological development. This requires continuous investments in research and development.

SWOT analysis for power electronics in Europe

INTERNAL	**Strengths:** - excellent technology and market position in the key component, the power semi-conductor device - excellent research infrastructure, leading position in R&D (universities, research institutes) - strong, trend-setting industry position on the system side e.g. in automotive, industry, energy, medical - well educated engineers, top experts in industry and academia - good structure and culture for cooperation in networks and clusters	**Weaknesses:** - lack of young engineers (students in electrical engineering) - transfer of innovations into products on the market sometimes slow or fails (slow innovation dynamics) - conservative approach with safety concerns leads sometimes to ´over engineering´ - only minor activities on passive components (R&D, production) - missing vertical integration required cross company cooperation to identify and quantify system advantages – this is often blocked by commercial boundary conditions (e.g. completely different in Japan)
EXTERNAL	**Opportunities:** - growing market due to increasing electrification of systems - new market segment e.g. micro power electronics (µPE) with energy harvesting or LED lighting - Industry 4.0 demands compact and efficient power supplies - new market segments in new applications based on WBG power electronics	**Threats:** - new competitors from Asia e.g. China - market distortions by unregulated subsidies in Asia and US - external players from Asia and US might be faster occupying the market, highly supported by government activities to push power electronics in these regions

3.2 Key Challenges for Europe Related to Wide Bandgap Power Electronics

To fully exploit the advantages of WBG power semiconductors on system level (mainly higher efficiency and higher power density), a system integration approach is necessary enabling the high switching frequency of >100kHz and the higher power density. The increase in power density leads to higher operation temperatures which can be easily handled by the WBG semiconductor material but not by today´s packaging and interconection technologies and the passive components. Therefore, new materials have to be developed for better thermal management, better electrical isolation and moisture protection. New packaging processes and technologies with very low parasitic inductances are required to enable fast switching frequencies >100kHz.

Key statements:

- *A major technical challenge is to cope with the extremely steep switching transients necessary for low switching losses and provide respective packing.*
- *Apart from the high switching frequencies of 100kHz up to the MHz range, the increasing power density on system level is key challenge.*
- *The overall economical challenge is to realise significant cost savings on system level despite higher WBG device costs.*
- *Finally, there is a psychological challenge to convince potential users that the new components and technologies are robust and reliable.*

3.3 Technology Gaps and Research Needs

WBG Materials and Devices

It is conventional to start any discussion on WBG materials with a table of fundamental material properties and to use a "figure of merit" to rank, for example Si, SiC, GaN, regarding their potential for high performance power devices. However, this approach is unrealistic in the face of the real practical fabrication challenges that compound semiconductor materials face.

Silicon is probably the most ideal engineering semiconductor material possible, very large almost perfect crystals can be grown and zero defect wafers produced. The electrical properties of Si can be modified by zero defect homo-epitaxy, ion implantation and annealing, and probably most important of all a native oxide (SiO_2) can be grown with an almost ideal interface with the semiconductor. Even though especially for SiC the same preconditions apply for the realisation of devices as we know for silicon (including the growth of a native SiO_2 oxide) the way to achieve a comparable maturity is still a long one.

In the case of SiC it is required to identify processes which could replicate deep doping profiles as possible in silicon by diffusion which is seen as a key technology to realise charge compensated high voltage devices. Since diffusion is not present in SiC and ion implantation depth is limited new approaches have to be investigated. Also the complete understanding of the SiC –oxide interface is in an infant stage compared to silicon, more research is mandatory to generate a complete picture. Assuming high voltage components based on bipolar concepts it will be an important topic to further improve lifetimes of minority carriers with the ultimate goal of introducing lifetime engineering techniques. Regarding material aspects one should strive for a more intensive research on alternative growths processes for reducing the substrate cost of today's PVT based material. Finally, in order to utilise the high temperature capabilities the modelling of SiC parts need to be refined, mainly material aspects above 200°C operating temperature are not yet completely analysed and implemented in predictive finite element tools.

For GaN/Si the details of the complex array of epitaxial layers to produce long-term electrically stable devices is yet to be finalised. One consequence of this lack of maturity is the fact that every manufacturers' device is unique and that there are no second sources. This severely inhibits the rate of commercial adoption of WBG technology by systems manufacturers. Again a case can be made for some co-operation in this basic technology area to accelerate its movement to maturity.

WBG System Integration

The evolution of power semiconductors has arrived at a level where packaging restricts the achievable performance of the final device. This statement already holds for today´s silicon technology and will get worse for wide bandgap power electronics with ultra-fast switching and high power density. A package for a power semiconductor has to remove the heat, provide secure insulation against the heat sink, conduct current and has to be electro-magnetically and thermo-mechanically reliable. The development of solutions for these multiple requirements has to be based on in depth knowledge of application demands as well as material and production processes.

The future developments in power electronics packaging have to face the following aspects:

- the increase of power density requires more sophisticated thermal design
- the possibility for higher junction temperatures can only partly be used due to the negative impact on reliability. But allowing a higher operation temperature would reduce system volume due to smaller heat sinks.
- more functions included in the package or module can reduce system costs
- steeper switching slopes force a more precise electro-magnetic design of the package and module and will influence the technology selection
- cost efficient production processes always remain an issue for improvements

<u>Key statements:</u>

Apart from WBG device development the WBG system integration is necessary to exploit the potential.

- *Packaging and system integration technologies enabling low parasitic inductances to master EMC issues*
- *Packaging and system integration technologies enabling reliability at higher temperatures*
- *Handling higher voltages on package/module level and system level**:** SiC in medium voltage (MV) applications e.g. in traction and industry*
- *Low inductance packaging and integration technologies: powerPCB with chip embedding, system-in-package (SIP), switching cell in a package*
- *Passive components for fast switching: mainly inductors, reduce losses at high switching frequencies, thermal management of (integrated) passives*
- *Characterisation, testing, modelling and reliability analysis of WBG packages, modules, converters*
  testing methodology: how to test highly integrated systems, key for cost effectiveness
  test stages and routines from chip to system, standards for system testing

4. Conclusions

After many years of (funded) research in SiC materials and device technology we see more and more devices entering the market from various suppliers in Europe, Japan and US. One might conclude that there is no more need for public funding. But the opposite is true. Research effort should be increased, as we see this in US with the new SiC programme announced by President Obama. Joint research should be extended from device technology to wide bandgap system integration involving all necessary technology and supply steps along the value chain of WBG power electronics.

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