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VYSOKÉ UČENÍ TECHNICKÉ V BRNĚ

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FAKULTA ELEKTROTECHNIKY
A KOMUNIKAČNÍCH TECHNOLOGIÍ

DEPARTMENT OF FOREIGN LANGUAGES
ÚSTAV JAZYKŮ

MARKET SURVEY OF HIGH POWER SEMICONDUCTOR DEVICES
PRŮZKUM TRHU VÝKONOVÝCH POLOVODIČOVÝCH SOUČÁSTEK

BACHELOR'S THESIS
BAKALÁŘSKÁ PRÁCE

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Bakalářská práce

bakalářský studijní obor **Angličtina v elektrotechnice a informatice**
Ústav jazyků

Student: Martin Jankovský ***ID:*** 168344
Ročník: 3 ***Akademický rok:*** 2015/16

NÁZEV TÉMATU:

Průzkum trhu výkonových polovodičových součástek

POKYNY PRO VYPRACOVÁNÍ:

Sestavte přehled trhu moderních výkonových polovodičových součástek včetně jejich řídících jednotek a systémů chlazení.
Zaměřte se na elektrické parametry a možnosti aplikace.
Na základě získaných informací se pokuste vzájemně porovnat produkty předních evropských výrobců (ABB, Eupec, Dynex, aj.).

DOPORUČENÁ LITERATURA:

Kaminski, N. “State of the art and the future of wide band-gap devices”, in Power Electronics and Applications, pp.1-9, Sept. 2009.

Millan, J. et al., "A Survey of Wide Bandgap Power Semiconductor Devices," in Power Electronics, IEEE Transactions on , vol.29, no.5, pp.2155-2163, May 2014.

Vobecky, J., "Design and technology of high-power silicon devices," in Mixed Design of Integrated Circuits and Systems (MIXDES), 2011 Proceedings of the 18th International Conference , pp.17-22, 16-18 June 2011.

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ABSTRAKT

Hlavním tématem práce jsou moderní výkonové polovodičové součástky. Jsou diskutovány i rozvíjející se materiály s velkou šířkou zakázaného pasu a jejich elektrické vlastnosti. Práce je pak zaměřena na tyto moderní součástky, včetně jejich teorie, aplikace a dostupnosti na trhu. Dále práce předkládá tabulky jednotlivých zařízení, které jsou nabízeny evropskými předními výrobci polovodičů.

KLÍČOVÁ SLOVA

Materiály s velkou šířkou zakázaného pásu, SiC, GaN, dioda, JFET, MOSFET, Tyristor, IGBT

ABSTRACT

The main topic of the work are modern high power semiconductor devices. Emerging wide-band-gap materials and their electrical characteristics are also discussed. The work is then focused on these modern devices, including their basics, application and availability on the market. Furthermore, the work presents the tables of the devices offered by the European leading semiconductor manufacturers.

KEYWORDS

Wide-band gap materials, SiC, GaN, diode, JFET, MOSFET, Thyristor, IGBT

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PROHLÁŠENÍ

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V Brně dne ....

(podpis autora)

PODĚKOVÁNÍ

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V Brně dne ....

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List of symbols and abbreviations

WBG – Wide-Band Gap

Si – Silicon

SiC – Silicon Carbide

GaN – Gallium Nitride

MOSFET – Metal-Oxide-Semiconductor-Field-Effect Transistor

JFET – Junction-Field-Effect Transistor

BJT- Bipolar-Junction Transistor

IGBT – Insulated-Gate Bipolar Transistor

$\mathrm{I}_{\mathrm{FAVM}}$ – Average Forward Current

V_{DRM} / V_{RRM}- Repetitive Peak Reverse and off-state Voltages

I_{TSM} / $\mathrm{I}_{\mathrm{FSM}}$- Non Repetitive Surge Peak on-state Current

I_{TAV} - Average on-state Current (SCR only)

$\mathrm{V}_{\mathrm{CES}}$- Collector to Emitter Voltage

I_{C} – Collector Current

I_F – Forward Current

Q_C - Total capacitive charge

$T_{j,max}$ – Maximum Junction Temperature

V_{DS} – Drain to Source Voltage

$\mathrm{R}_{\mathrm{DS\,(on)}}$ - Drain- source on- state resistance

I_D – Drain-Source Current

$\mathrm{P}_{\mathrm{tot}}$ – Power Dissipation

$\mathrm{I}_{\mathrm{Dpuls}}$ – Pulsed Current, Drain-Source

Introduction

High power semiconductor devices find their role in almost every segment of electronics industry. The well-established Silicon has always been the preferable option for manufacturers. Nowadays, more advanced semiconductor materials, also known as wide-band gap materials, show a promise to replace Silicon. The first chapter of the work is focused mainly on the currently used WBG materials, such as Silicon Carbide and Gallium Nitride. Their electrical characteristics and technological portfolio are also discussed.

Power semiconductor devices can be generally classified as majority carrier devices and as minority carrier devices. The former include Schottky diode, power metal-oxide-semiconductor field effect transistor (MOSFET) and junction field-effect transistor (JFET). Current in these devices is carried mostly by majority carriers. The minority carrier devices are represented by PIN diode, bipolar junction transistor (BJT), thyristor and insulated-gate bipolar transistor (IGBT). The basics of these devices are explained in the second chapter of the work.

The aim of the third chapter is to explain power module, to which components are connected. The chapter also presents the issue of heating and different approaches to it. Partial Discharge phenomenon occurring in the high power devices is also mentioned.

The role of the high power semiconductor devices is explained in the fourth chapter of the work. Three main areas of application are Grid applications, Hybrid and Electric Cars and Railway Traction. Different power devices are discussed in the practical applications in the field.

The final two chapters are the focus of the work. They are dedicated to review of particular high power semiconductor devices currently available on the market. In this par, the work also presents the devices offered by leading European semiconductor device manufacturers (ABB, Infineon, Dynex, and Semikron). The devices in the sixth chapter are organized into tables and special attention is paid to their electrical properties. The individual devices were selected with regard to the maximal values characterizing the devices offered by the company. The tables are arranged so as to enable the comparison to the reader.

1 Wide-Band Gap Semiconductor Materials

Wide-band gap semiconductors, with their superior material properties, have emerged as a powerful solution for power electronics. Silicon shows some limiting factors, namely its blocking voltage capability, operation temperature and switching frequency. The effectiveness of power devices is then reduced by these ineluctable physical limitations [1]. At present, silicon carbide (SiC) and galium nitride (GaN) demonstrate the most promising results, both in terms of their theoretical characteristics, commercial availability and maturity of technological process.

1.1.1 Band Gap

The crystal bonds of wide-band gap materials are stronger than in Si and therefore more energy (Eg) is needed to break an electron out of the bonds. “Wide” band gap refers to a material with a band gap of usually 3 eV (electronvolt). The band gaps of SiC and GaN are 3.0 eV and 3.4 eV respectively, which is significantly greater than the bandgap of more commonly used semiconductors like silicon (1.12 eV) and gallium arsenide (GaAs, 1.42eV).

1.1.2 High temperature operation

Because more energy is necessary to cross the band-gap, the intrinsic carrier concentration n_i is lower than in silicon, and is exponentially dependent on the band gap and temperature. The leakage currents are (theoretically) much smaller than in silicon due to being proportional to n_i or ${n_i}^2$, and much higher temperature is needed for compensation of these currents. Therefore, wide-band gap devices are able to operate at higher temperatures [2].

1.1.3 Diffusion Voltage

Threshold voltage for silicon device is about 0.7 V. WBG devices have much higher threshold voltage. In SiC, with the same current density, the forward voltage drop of a wide-band gap PN-junction is 3 V. For SiC PIN diode, this drawback can be compensated by drift zone width corresponding to devices blocking several kilovolts, which will cause a smaller voltage drop. However, application for high temperature and high current operation of unipolar devices is less attractive due to a strong positive temperature coefficient of the forward voltage drop. On the other hand, electron-hole-plasma-modulated devices (PIN diodes, thyristors, IGBTs) show reasonable positive temperature coefficient. These devices have very high concentration of both holes and electrons due to the enhanced conductivity modulation effect created by enhanced injection; hence the name. They have a superiority over unipolar devices even at lower blocking capabilities [2].

1.1.4 Peak saturation velocity

Another important parameter of a wide-band gap material is its peak velocity, to which the high-frequency switching capability is proportional. Due to more than twice the peak velocity of Si, WBG semiconductor-based devices can be switched at higher frequencies. Besides that, charge in the depletion region of a diode is removed faster. Consequently, the reverse recovery current of the WBG semiconductor-based diodes is smaller, and the reverse recovery time shorter [3].

1.1.5 Breakdown voltage and width of the drift zone

The high critical field E_c influences the impact ionisation and avalanche breakdown of the device. The breakdown voltage V_{BV} depends also on design dimension, the concentration of N_D and N_A. The formula of the breakdown voltage for the non-punch through case is:

$$V_{BV} = \frac{1}{2} \cdot w_{drift} \cdot E_c \, . \qquad (1)\ [2]$$

For the same breakdown voltage, much higher doping levels can be achieved, so device layers can be thinner. The drift zone width of a WBG device is of order of magnitude smaller (see Figure 1) than that of a Si device [3] [4].

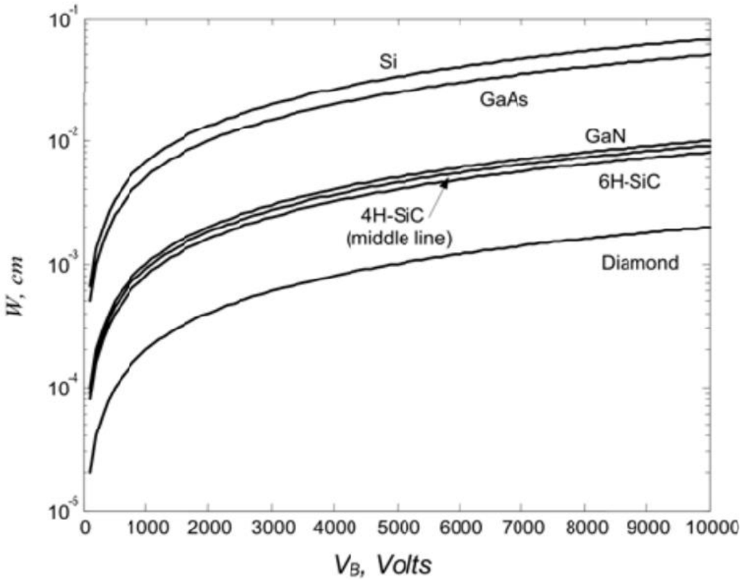

Figure 1: Width of the drift zone of semiconductor materials at different breakdown voltages [3]

1.1.6 Specific On-resistance

Since high critical field E_c, concentration N_A can be increased with much higher V_{BV}. In the case of unipolar devices, for example Field Effect Transistor, greater depletion doping keeps the region thinner, therefore majority carriers pass through a shorter distance from drain to source, ultimately reducing specific on-resistance. The specific on-resistance of the drift region of the SiC and GaN devices is approximately 10 times lower than for their Si counterparts (see Figure 2). The specific on-resistance ratio between Si and WBG semiconductor materials increases with a growing breakdown voltage [3] [4].

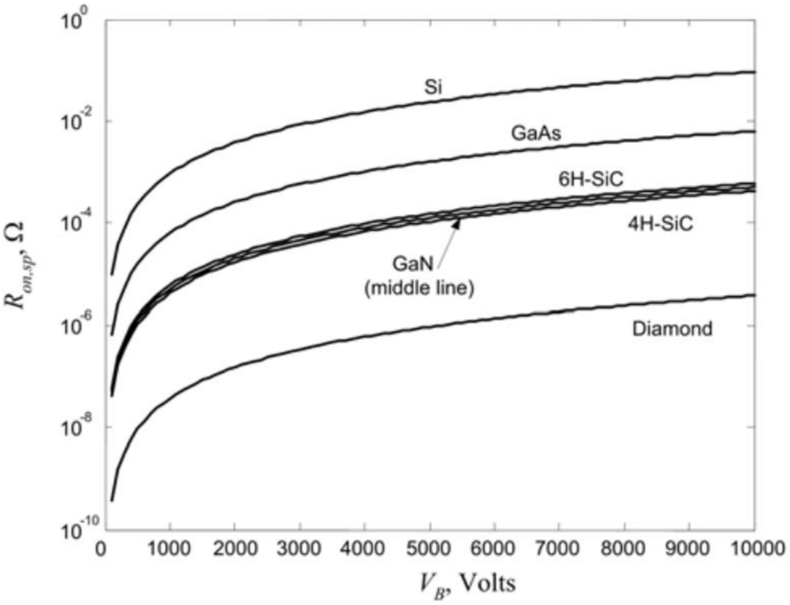

Figure 2: Resistance of the drift region of semiconductor materials at different breakdown voltages [3]

1.2 Silicon Carbide

The quality of the crystal, the size of the wafer and cost per area are the key elements for all wide-band gap semiconductors. The current status of Silicon, which is almost defect free, 200-mm in diameter and which price is approximately 0.10 €/cm² took several decades of developing [2]. Improvement of silicon carbide technology over the decades has moved from research to production. 100-mm SiC wafers are already available in the market, while 150-mm are in the stage of development [1].

1.2.1 SiC vs Si

The on-resistance for a given chip area is lower for SiC device compared to its silicon counterpart due to high breakdown electric field. The maximum junction temperature is a temperature at which the device can operate. SiC can operate at temperatures up to 400 °C in the long term. However, SiC device junction temperatures will be limited to values of 250 °C (short term) because of packaging considerations. Nevertheless, compared to Si, with its maximum junction temperature of 150 °C, it is a considerable improvement. Moreover, SiC device operating at 250 °C should be more reliable than Si device operating at its theoretical maximum temperature [5].

Due to its superior physical characteristics, SiC is one of the most promising semiconductor materials for power switching applications. Compared to Si diodes, the high thermal conductivity of SiC is a significant addition as it enhances heat conductivity and increases power level. The size of the cooling systems is therefore minimized [1] [6]. SiC devices are smaller, lighter and more compact, which makes them suitable for high voltage power applications.

1.3 Gallium Nitride

GaN impresses mainly because of its wide-band gap, large critical electric field, high electron mobility and fairly good thermal conductivity. Therefore, it finds its use in high-voltage, high-frequency, and high temperature applications. Presently, the material is in a early stages of power applications, however, the photonics area already introduced GaN-based devices to the market [1]. In case of power electronic devices, GaN based high electron mobility transistors (HEMT) shows promising results.

1.3.1 GaN technology portfolio

GaN epilayers are mainly grown on sapphire, Si and Sic substrates as commercial high-quality freestanding GaN substrates are rather difficult to grow. High-quality, single-crystalline GaN films are necessary for power conversion. GaN epilayers grown on sapphire are suitable for LEDs and other optical applications, while GaN on the SiC is attractive for power applications [3]. However, of all mentioned, GaN on Si substrate presents cost advantages.

The basic GaN based device structure is high-electron mobility transistor (HEMT). Organometallic vapor phase epitaxy (OMVPE), which is a chemical vapour deposition method to produce single or polycrystalline thin film [7], has matured dramatically over the years. The first device structures were based on a 0.5μm optically defined gate. One option for field plate design is to extend the gate metallization into the gate-drain access region in order to form a gate connected field plate and a source connected field plate is additionally formed over top of this gate structure. Device breakdown of voltage is then in excess of 300 V. Superior thermal conductivity, low-temperature-related memory effects and high power density compatibility make SiC the preferred substrate. A baseline GaN device consists of a thin GaN cap with an AlGaN barrier on a GaN buffer (see Figure 3) [8]. As a result of piezoelectric effect due to the large conduction band discontinuity, and natural polarization effect, high-density two-dimensional electron gas (2DEG) accumulates between the boundary layers of GaN and AlGaN, leading to a low on-state resistance [9].

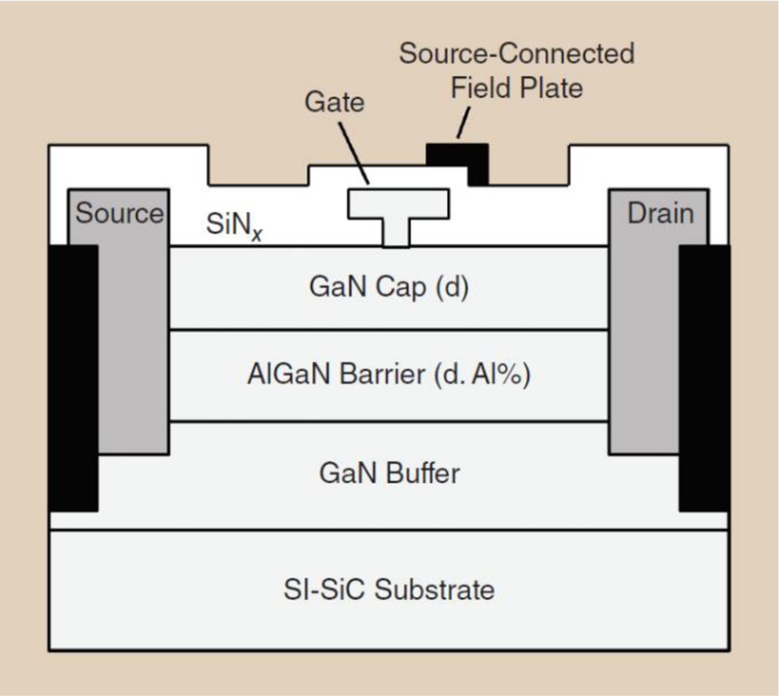

Figure 3: AlGaN/GaN device layer structure on semi-insulating SiC substrate [8]

Several studies report that GaN based power devices have comparable performances as SiC based device, moreover, for a lower price. A device specific on-resistance for a given reverse hold-off voltage capability is substantially lower owing to high electron mobility and high bandgap [10]. Because of a lower R_{ON} and faster switching speed than in Si counterparts, power conversion efficiency and miniaturization of the system can be achieved.

	Si	**6H-SiC**	**4H-SiC**	**GaN**
Bandgap (eV)	1.11	3.03	3.26	3.45
Dielectric constant	11.9	9.66	10.1	9
Breakdown field $(\boldsymbol{kV/cm})$	300	2500	2200	2000
Electron mobility $(\boldsymbol{cm^2/V \cdot s})$	1500	500	1000	1250
Hole mobility $(\boldsymbol{cm^2\ /\ V \cdot s})$	600	101	115	850
Thermal conductivity $(\boldsymbol{W/cm \cdot {}^\circ C})$	1.5	0.46	4.9	1.7
Saturated E-Drift Velocity **($\times$ $\boldsymbol{10^7}$ cm/s)**	1	2	2	2.2

Table 1: Table of Semiconductor Materials

2 Basics of Semiconductor Devices

2.1 P-N Junction

PN junction represents the fundamental building block of semiconductor technology. PN junction is formed by joining N-type and P-type material together, one material with the majority carriers of electrons and the other with the majority carriers of holes.

When the two materials are joined, majority carriers of both types close to the metallurgical junction diffuse across the junction into the opposite part where they change to minority carriers. Only the ionized dopants are left in the region, positive ions donors in N-type and negative acceptor ions in P-type. The result is the lack of free carriers in the region near the junction. This region is called the depletion region. [11]

2.1.1 No-applied bias

When no voltage is applied, minority carriers of the N-type material within the depletion region will pass into the P-type material. In case of majority carriers in the N-type material, i.e. electrons, the attractive forces of the layer of positive ions in the N-type material and shield of negative ions in the P-type material must be overcome for migration of electrons to the N-type material. However, only a small number of majority carriers have adequate kinetic energy to migrate into the P-type material due to the large number of majority carriers in the N-type material. The same rules apply for the majority carriers of the P-type material. Therefore, the current under no-bias conditions is zero [11].

2.1.2 Reverse bias

When a negative bias is applied across the PN junction, i.e. negative terminal is connected to the P-type material, a large number of electrons are drawn to the positive potential of the applied voltage, which results in the increase of the uncovered positive ions in the depletion region.

Similarly, an increase in the number of uncovered negative ions in the P-type material occurs. This causes the widening of the depletion region, which eventually establishes a too great barrier for the majority carriers to overcome. The flow of the majority carriers is then reduced to zero. However, the number of minority carriers entering the depletion region will not change. This current, represented by minority carriers, is called the reverse saturation current [11].

2.1.3 Forward bias

When a forward bias is applied, electrons of the N-type material and holes of the P-type material will recombine with the ions near the boundary and the width of depletion region will be reduced. The magnitude of minority-carrier flow of both materials has not changed. However, the reduced width of the depletion region leads to a heavy majority flow across the junction. The width of the depletion region will continue to decrease with the increasing magnitude of the applied forward bias. The result is the exponential rise in current [11].

2.2 Schottky Rectifiers

A Schottky-barrier devices utilize a metal-semiconductor junction. The semiconductor is frequently of N-type silicon, while metal is either molybdenum, platinum, chrome or tungsten. The majority carrier of both materials is electron.

When the two materials come into contact, the electrons of the N-type material instantly migrate into the metal, building a heavy flow of majority carriers. These injected carriers are called "hot carriers" because of their very high kinetic energy compared to the electrons in the metal.

A region near the junction surface depleted of carriers in the semiconductor material is created, similarly to the depletion region in the PN junction diode, as a result of the heavy flow of electrons. Moreover, a "negative wall" is established in the metal at the boundary between the two materials by the additional carriers in the metal. The net results in a "surface barrier" that prevents any further current. In other words, electrons of the semiconductor materials face a carrier-free region and a negative wall [11].

When a forward bias is applied, the strength of the negative barrier is reduced due to the attraction of the applied positive potential of the electrons. This leads to a heavy flow of electrons through the boundary. The magnitude of the flow is controlled by the level of applied voltage [11].

2.3 Power MOSFET

Unlike in bipolar transistors, the current in unipolar devices is transported only by majority carriers. The switching speed in power MOSFET devices is therefore faster as they do not have minority carriers that should be transported during turn-on and turn-off. The only limitations are internal capacitances that are charged and discharged when the device turns-on and turns-off. Positive temperature coefficient of the internal resistance allows an easy paralleling of devices [12] .

The drawback of the MOSFET of the planar structure is the inability to satisfy the needs for both high voltage operation and high current control. However, through the vertical structure, such as VMOS or UMOS, the electrical field of the device is not dependent on the channel and current density is increased by removing the drain electrode from the surface.

Vertical structure means that the channel is formed in vertical direction, thus the current flows in vertical direction rather than in horizontal as it is in the planar devices. Several improvements of vertical structure were demonstrated, although most were abandoned in favour of Vertical Double Diffused MOS (VDMOS). The gate is built over the drift zone N^- and both die and field plate are metallized, leading to a better thermal resistance. However, the disadvantages are a bigger gate access resistance and a higher interconnection capacitance [13].

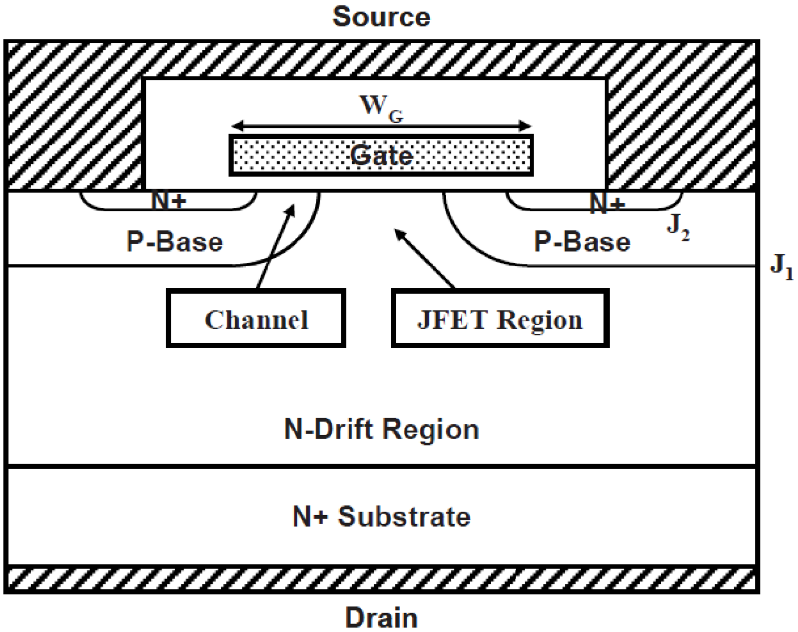

Figure 4: VDMOSFET structure [12]

The current is carried by electrons for N-type power MOSFET, and by holes for P-type power MOSFET. The channel is the main part of the power MOSFET. Electrons are injected by N^+ source and the channel is driven by the gate. When $V_{DS} > 0$, injected electrons are moved through the drift zone and raise the N^+ zone and the drain. When no voltage is applied, the gate stops the electron injection and MOSFET turns-off [12].

2.4 IGBT

While BJTs show a low voltage drop, the base drive needs a drive current; and while power MOSFETs show very fast switching operations, are strong in overload operations and the gate drive requires very low energy, the internal resistance of the MOSFET is high. This results in a large voltage drop. The merger of physic of operation of bipolar and MOS transistor enabled the creation of Insulated Gate Bipolar Transistor (IGBT) in 1980s. IGBT is characterized by the high power density, simple interface, and ruggedness, which make the device ideal for all medium and high power applications [13].

The structure of IGBT can be viewed as SCR with a cathode short and a MOSFET (a DMOS transistor connecting the N^+ -cathode to the N^--base.) It can be also viewed as a DMOS transistor with an extra P-N junction with the drain region. Vertical IGBT consists of P^+ anode of low-resistivity substrate material and the N^--epitaxial layer. Isolation is difficult for this structure, therefore devices are dices as discrete components. Anode of IGBT of lateral structure is united at the surface and is isolated from substrate by the P-type material. [6]

The N-bulk layer is lightly doped and serves as a drain of DMOS transistor and as a base of the P-N-P bipolar transistor. In the on-state, excess electrons are injected from the N^+-cathode via DMOS transistor surface channel and excess holes from the P^+-anode [6].

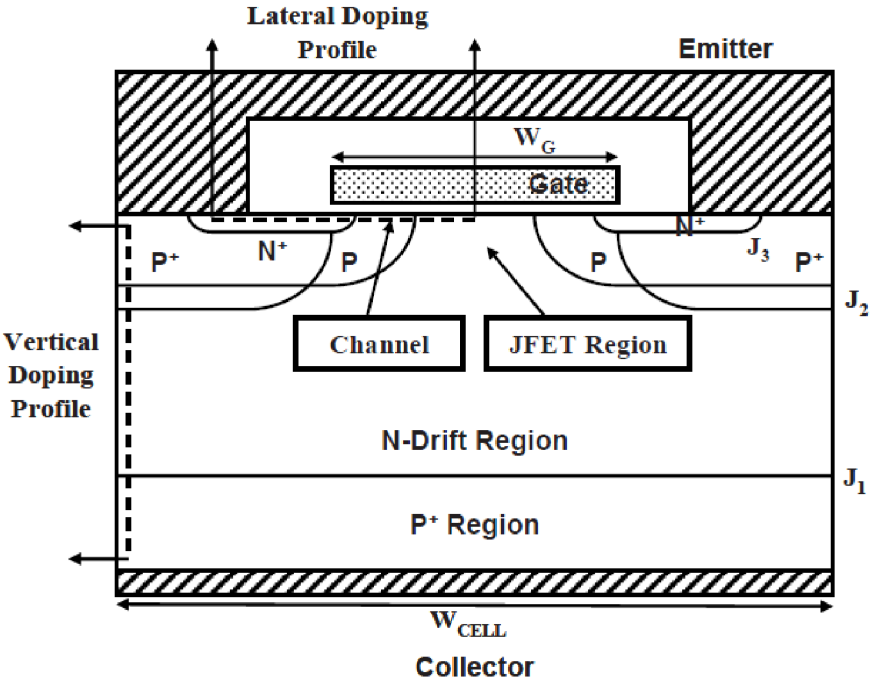

Figure 5: IGBT structure [12]

When a negative voltage is applied to the collector, junction J1 becomes reverse-biased and junction J2 is forward biased. The depletion region in the N-base region of J1 extends toward junction J2 [6].

If a positive voltage is applied to the gate of the structure, an inversion layer channel under the gate electrode is created, connecting the N+ emitter region with the N-base region. Electron current is thus transported from the N+ region to the N-base region if a positive bias is applied to the collector of the structure. The electron current serves as a base drive current for the PNP transistor and consequently the holes are injected from the P+ collector/N-base junction J1, creating the emitter current of the PNP transistor. Current flows from the collector to the emitter with a bipolar component associated with the wide-base PNP transistor and a unipolar component via the channel of the MOSFET region [6].

A slight increase of gate bias above the threshold voltage of the MOSFET region leads to pinch-off conditions, hence limitation of the electron current delivered to the N-base region. Because this limits the base drive current for the PNP transistor, its current also becomes saturated. The device is thus able to exhibit an active region with the collector current saturated at a value determined by the applied gate bias [6].

2.5 Thyristor

Thyristor can be viewed as a multi-layered P-N-P-N device, having three P-N junctions, J1, J2 and J3 in series (see Figure 6). The N1-layer (N-base) is wider than other regions and has the lowest doping level. The contact electrode to the outer P-layer is called the anode, and similarly, the contact electrode to the outer N-layer is cathode. The gate electrode is connected to the inner P-layer [14].

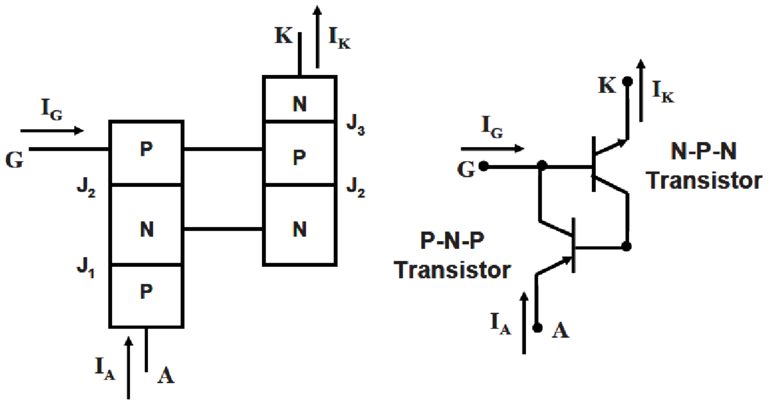

Figure 6: Transistor equivalent circuits for the power thyristor structure [12]

When a positive current pulse is applied to the gate, thyristor starts to conduct and continues to do so until it is forward biased. Thyristor can switch from a high-impedance and low current off-state to a low-impedance and high current on-state, or vice versa. Thyristor has therefore three operational modes: reverse blocking mode, forward blocking mode and forward conducting mode [12].

If a negative voltage is applied to the anode, the junction J1 and the junction J2 become reverse biased and junction J2 becomes forward biased. Both sides of the junction J3 have high doping concentrations, thus thyristor is capable of supporting less than 50V. Most of the negative bias is supported by the junction J1 [12].

If a positive voltage is applied to the anode, the junction J1 and J2 become forward biased, while the junction J2 becomes reverse biased. The applied positive bias is supported across the N-drift region [12].

The blocking voltage capability is defined by open-base transistor, not by avalanche breakdown. The same applies for the reverse-blocking operation. The reverse- and forward-blocking capability of the thyristor structure are relatively equal, which makes them appropriate for AC power circuits [12].

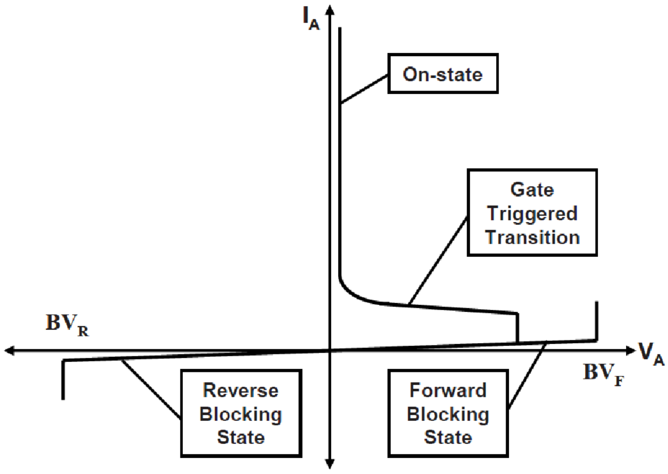

Figure 7: Output characteristics of the power thyristor structure [12]

2.6 High Electron Mobility Transistor

High Electron Mobility Transistor is a heterostructure field-effect transistor. The first HEMT devices utilized modulation-doped AlGaAs/GaAs heterostructures. In this case, electrons are concentrated in the heavily doped N^+ AlGaAs.

The basics of HEMT is the heterojunction of heavily doped N^+-AlGaAs (the barrier layer) and lightly doped P^--GaAs (the channel layer). The conduction band edge of the barrier layer is energetically higher when compared to the band in the channel layer.

When the materials are brought together, under the thermal equilibrium condition, the Fermi levels in the two materials must be aligned at the same horizontal position throughout the entire structure (see Figure 8) [15].

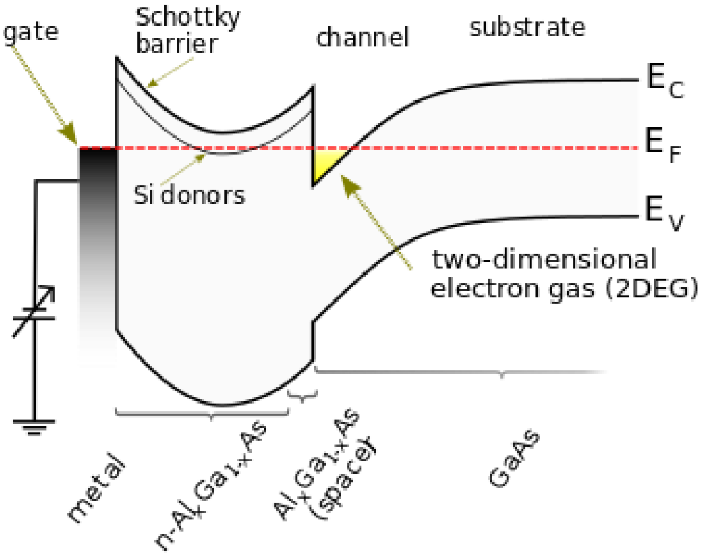

Figure 8: Band diagram of HEMT [16]

Electrons are moved from the heavily doped barrier layer to the lightly doped channel layer due to the reduction of gradient of the electron concentration on the barrier layer and due to the tendency of electrons to occupy the lowest allowed energy state. The result is the very narrow potential well near the heterointerface on the channel layer side with electrons with high concentration and high mobility, hence the name Two Dimensional Electron Gas (2DEG) [15].

3 Power Electronic Modules

3.1 Module

The traditional module (see Figure 9) consists of five layers of different materials, linked to the others by a thin transition – an interface. The layers are put together by welding or brazing. The joints have low thermal conductivity, which degrades the dissipation of the heat generated by the chip [13].

The first broadcaster must have good electrical conducting properties, because it is directly under the chip, and thus performs the electrical connection. The layer must also be a good heat conductor since it allows the flow of heat generated in the chip to spread. Copper is ideal for the layer, as it combines the two properties [13].

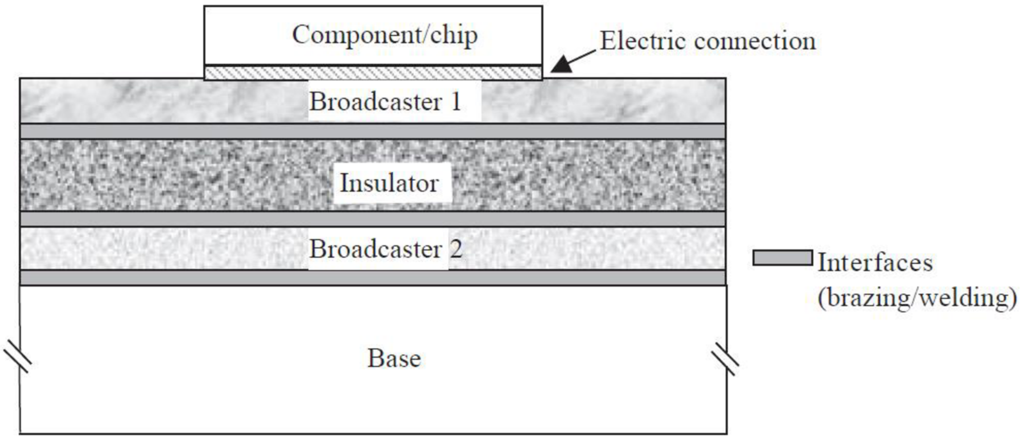

Figure 9: Cross section of Power Module [13]

The first broadcaster is then connected to the electrical insulator that electrically isolates the components from the rest of the module. It provides further electrical insulation between the various components of a single module when semiconductor devices are mounted in parallel, as it is common for IGBTs. It must be a strong insulator but must also have enough thermal conductivity for heat evacuation. And lastly, good combination capabilities with copper are essential. The most commonly used material for this purpose is aluminium nitride (AlN) [13].

The second broadcaster offers mechanical support, its rear provides a link with the outside environment, and is a link with the base. Copper is the material of choice for this layer. The module is covered with silicon and encapsulated in plastic casing, excluding the rear of the base which exchanges the heat with the outside world [13].

3.2 Cooling

The principle for a cooler is to submit a maximum exchange surface with a fluid that will absorb the heat. Natural convection is a heat transport due to the difference in temperature within a space. However, convection can be forced. In forced convection, the heat transport is inflicted by external force, such as pump or fan [13].

Semiconductor failure mechanisms are temperature dependent. The lower the junction temperature, the higher the reliability of the device. The junction temperature is dependent on the power dissipated in the device and thermal resistances/impedances [17].

The heat generated in a semiconductor chip follows various paths. While small signal devices do not usually require heatsinks, as the heat flows to the mounting base that is close to the case, power transistors are mounted on heatsinks due to the high power dissipation. The heat flows from the transistor case to the heatsink, which loses heat to the surroundings by radiation and convection, or by conduction to cooling water [17].

The traditional coolers for power electronic devices are air type, forced convection, or water type. Water attracts due to its very good thermal capacity and its simplicity of use. It is used in a closed loop, under the condition that the increase in temperature between the input and output is controlled. However, because of its poor electrical insulating properties, the establishment of an electrical insulator between the base and the cooler is often necessary [18].

One possibility how to avoid this insulation layer is to deionize water. Another is to use dielectric fluids (inert fluor, liquid nitrogen, etc.). For instance, Hybrid Electric Vehicles utilize fluid cooling for power switching devices in DC/DC power converters. However, they make up nearly a third of the volume and weight of DC/DC converters. The design of heatsinks is thus important to gain high power-to-volume and high-power-to weight ratios [13] [18].

SiC based devices have advantages of size and loss reduction which allow low switching loss and the possibility of simpler and smaller cooling structures. For instance, the 15kV Sic IGBT can be switched at higher switching frequencies, compared to its Si counterpart. At 10kV blocking voltage and 5A current, to ensure safe thermal margin, the 15kV/20 A SiC IGBT switching at 6.2 kHz is cooled with liquid, while at 5.1 kHz with forced air cooling [19].

Heatsinks can be divided into three types; flat plates, diecast finned heatsinks, and extruded finned heatsinks. They are normally made from aluminium or copper. The simplest types are flat plate sinks to which a transistor is attached. The thermal resistance is dependent on the thickness, area and orientation of the plate, but also on the finish and power dissipated [17].

3.3 Partial Discharge

Another phenomenon that often occurs in the high power modules is partial discharge. It is a localized electrical discharge that partially bridges the insulation between conductors. It is created by the presence of high voltage in the insulation or on its surface [20].

During the phenomenon, impulse conversion of some electric energy to mechanical energy in the form of an acoustic emission wave takes place [20]. Moreover, the partial discharge increases with higher frequencies. This can results in the damage of high-voltage devices, such as inverters with IGBT modules, which are used to generate sinewave output from high DC voltage [21].

Currently, there are several methods to monitor the development of partial discharge. Among them is DGA (Dissolved Gas in oil Analysis), UHF (Ultra High Frequency) and Acoustic Emission (AE) [20].

4 Application of Power Semiconductor Devices

Power semiconductor devices are the heart of any power electronic converters. Their application range from low power supplies, such as microwave devices handling about 100 W, to high power system, such as HVDC or locomotive drives of several MW. The figure shows the application for these power semiconductor devices as a function of operating frequency. As can be seen, the power rating decreases with the increasing frequency (Figure 10) [12].

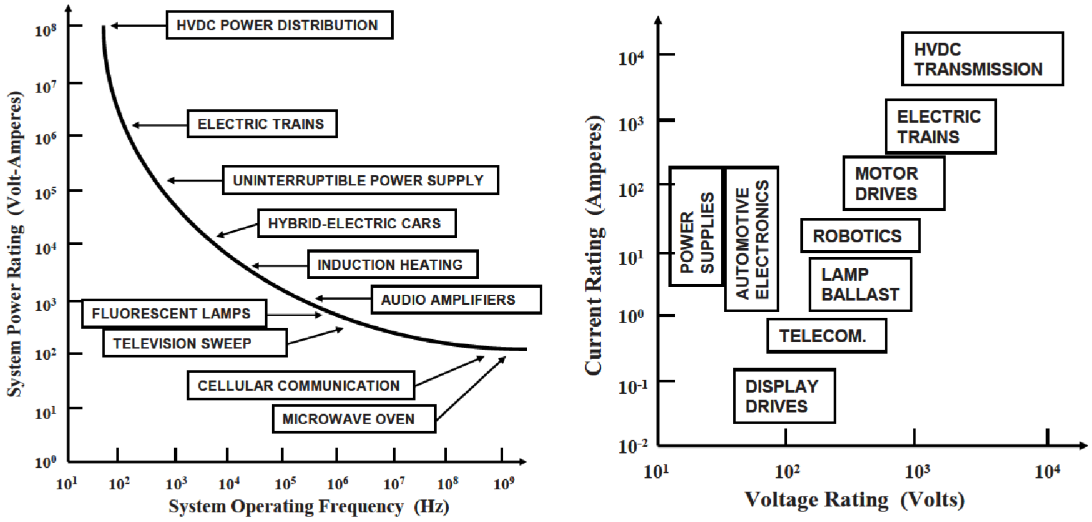

Figure 10: Applications and System ratings of power semiconductor devices [12]

The next figure shows the classification of power devices regarding their current and voltage requirements. HVDC power transmission and locomotive drive devices have to be capable of control of over 10MW of power. Therefore, thyristor which can handle more than 6000 V and 2000 A is suitable for this area of application. IGBT devices are the preferable option for applications that require operating voltages about 300 and 3000V and moderate current handling capability. Discrete power MOSFETs are, on the other hand, appropriate for such applications as automotive electronics or switch mode power supplies [12].

4.1 Grid Applications

The very high power end applications portray only a small, nevertheless important market sector of semiconductor components. Their progress is determined by the technologies created originally for lower power application. These technologies are then scaled and optimized in order to withstand higher voltages and currents [22].

Current grid systems must deal with the large energy demands of highly populated and industrializes areas. Furthermore, power must be often delivered from remote energy generation locations that use alternative energy sources, like wind turbines, solar cells or hydro plants. The two main systems include High Voltage Direct Current (HVDC) transmission and Flexible AC Transmission Systems (FACTS). Three devices are used in the Megawatt range, the Phase Controlled Thyristor (PCT), the Insulated Gate Bipolar Transistor (IGBT) and the Integrated Gate Commutated Transistor (IGCT). The power diodes are also used for rectification, snubber and freewheeling purposes [22].

HVDC transmission systems are used when electrical energy is transmitted over large distances in DC rather than AC form. Current Source Converters (CSC) and Voltage Source Converters (VSC) are used for the AC/DC conversion. The system of choice depends on the distance of transmission and the amount of power [22].

PCT based CSC topologies with their overall low system losses are broadly employed for long distances and multi-Gigawatt power level, whereas, IGBT based VSC conversion is applied for shorter distances and sub-Gigawatt power levels because of a number of integration and control features. Static Compensators (STATCOM) for voltage stabilization and load balancing, grid interties, energy storage, and active filters are used on the AC side, resp. in FACTS. They all utilize both IGBT and IGCT based VSC topologies [22].

Power semiconductor devices used in grid systems are not different from the devices used in other power applications. However, these devices operate at voltages of hundreds of kilovolts. In order to support the total dc-line voltage, grid power semiconductor devices are normally connected in series. Performance/cost calculation of a given topology and operational parameters determine the choice of device. For example, lower voltage rated devices have a benefit of lower overall losses. However, they require larger number of component and accessories to reach the desired voltage level [22].

4.2 Hybrid, Electric and Fuel Cell Vehicles

In pursuance of lower Co2 emissions, as road traffic has a contribution of 23%, automobile OEMs are forced to increase the market share of electric vehicles. The electric vehicles are required to be on the similar level with combustion engine cars in terms of price, driving range, maintenance effort, lifetime and safety [23].

A new architecture with new power electronic system is proposed (see Figure 11). A high voltage battery allows driving current applications, such as air conditioning compressor, water/oil pump) with higher voltage to reduce costs and increase effectiveness [23] .

IGBTs and freewheeling diodes have a critical role in hybrid, electric, and fuel cell vehicles, particularly in electric traction inverters, voltage boost dc/dc converters, fuel cell air compressor motor drives, and other on-aboard power management converters. Furthermore, low-voltage power MOSFETs and power integrated circuits are widely utilized in engine control, vehicle dynamic control, vehicle safety, and body electronics subsystems in electric and conventional internal combustion engine (ICE) vehicles [24].

The task of the main inverter with the IGBT power module is to control the energy flow between the energy storage and the electric motor. The power modules in the main inverter must overcome harsh environmental conditions, like severe temperature cycles, moisture, and mechanical stress through vibration or shock. Efficiency of the inverter is therefore vital not only because of its influence on fuel economy and driving range, but because its failure could lead to immobilization of the vehicle as well as a safety risk. Reliability, the highest power density, and low cost are thereupon the main technical requirements for IGBT modules [23].

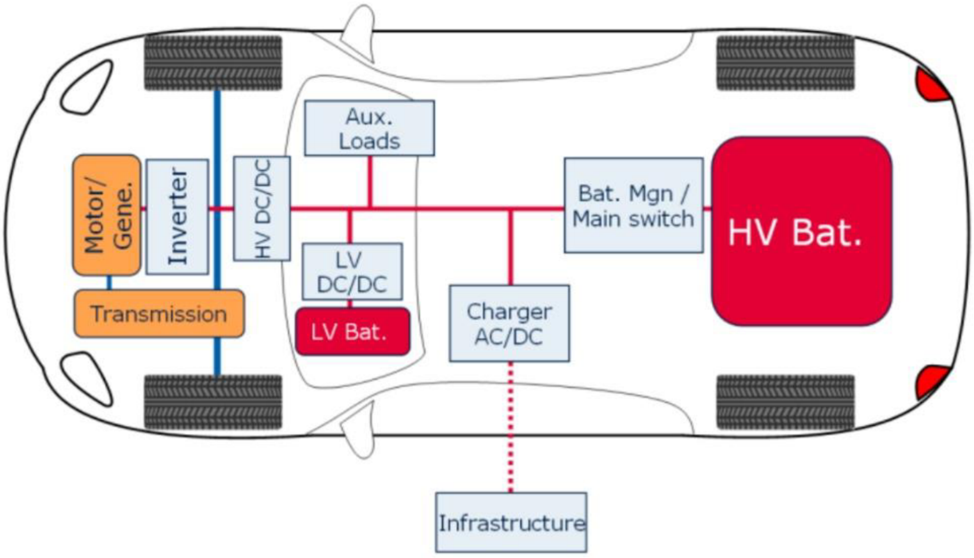

Figure 11: Electric Vehicle Architecture [23]

For the costs minimization and the best use of battery, the efficiency of the main inverter must be increased. Reduced power losses enable smaller inverter size and reduced cooling effort. This can be achieved by optimization of both the front-end (power semiconductor) and back-end (power module) technology [23].

4.2.1 Size and cost reduction

In order to reduce cost and size of the main inverter, Infineon has developed the HybrdiPACK™ Light A six-pack module (705V/200V) is based on the HybridPACK™ 1 and is aimed at automotive inverter application up to 20kW. The system assembly is the same as was the older module, and so is the nominal current. However, the blocking voltage of the IGBT was increased by 50V, size was reduced by 60% and weight by 70% [23].

4.2.2 Increase of power density and efficiency

Another trend is to increase power density and efficiency. HybridPACK™ Drive is a more compact six-pack module (750V/660A) with power levels in the range of 50kW – 100kW. The module utilizes the new EDT2 technology. The blocking voltage is 100V higher, the size of the module is reduced by 30% and the module allows a 10% higher rated current when compared to the predecessor module, HybridPACK2, with the previous IGBT technology. The module uses the direct cooling concept with pin-fins that significantly improve the thermal cycle capability and extend the lifetime of the power module [23].

4.3 Railway Traction

The progress of power electronic technology has been the means for the on-going evolution of railway traction equipment, for both the traction drives on board the trains and the traction power supply systems on the track side [26].

In modern electric railway traction, AC traction drives based on IGBT has replaced DC traction drive in order to use the advantages of 3-phase induction motors or synchronous motors [26].

The current traction drives for AC railway line include a three phase Voltage Source Inverter, which supplies the traction motor, and a step down transformer associated to an active front end rectifier (see Figure 12). It operates at the network frequency (50Hz or 16.7Hz) and fits the voltage level regarding the DC bus. Today, 3.3kV or 6.5kV IGBT modules with the corresponding DC bus voltages of 1.8kV and 3.6kV respectively are used. While the input transformer has to sustain the high voltage constraint, all the semiconductor devices are connected on the low voltage side which brings the benefit with regards to the insulation of the cooling system [27].

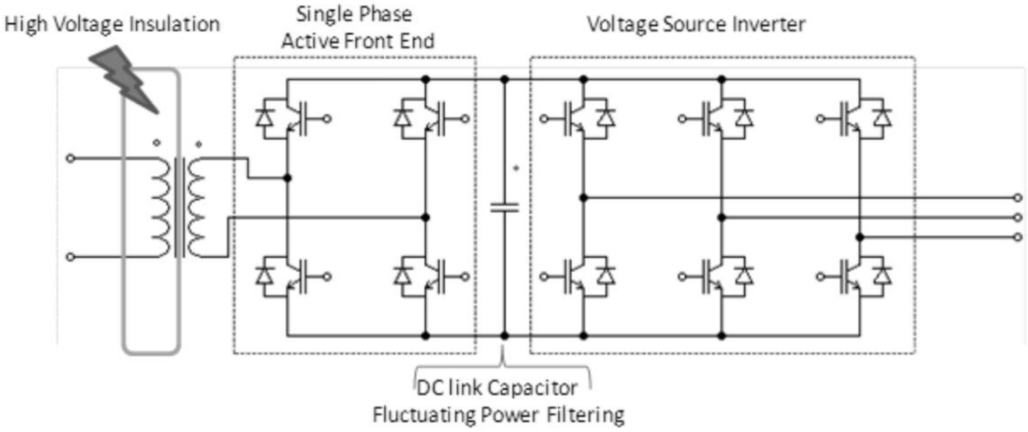

Figure 12: Converter for railway traction [27]

With the Silicon reaching its limit, drive manufacturers must consider the new SiC technology. Nowadays, 1.2kV and 1.7kV SiC MOSFET modules are offered by several manufacturers [27]. For instance, French company Alstom has launched Osiris project focusing on Metro in Milan, principally it regards the auxiliary and battery charger. The application utilizes full SiC three phase inverter consisting of full bridge chopper (MOSFET SIC), medium frequency transformer and SiC diode rectifier. SiC devices are supplied by American Cree [27]. Additionally, 10kV dies (MOSFETs and diodes) are already available and may be a solution to the replacement of the bulky input transformer.

5 Power Semiconductor Devices

Fundamental components of power electronics are electric power converters and high power semiconductor devices. These solid state devices can be divided according to their functions. The first is a switch, to control the flow of current delivered to the load. The second is a rectifier.

With regards to future technological innovation of power semiconductor devices, there are two concepts. The first is to improve the low-loss characteristics and to miniaturize the electric power equipment. The other concept is to expand breakdown voltage and current. In terms of Si, it initially started as a bipolar junction transistor (BJT), developing to a metal-oxide-semiconductor FET (MOSFET), next to a gate turn-off thyristor (GTO), and finally to an insulated gate bipolar transistor (IGBT). The problem is that as long as power devices are based on Si, these expansion are considered problematic [28].

For example, in a bipolar device Si IGBT, the conduction modulation effect by hole injection is utilized in favour of reduction of on-resistance retaining high voltage blocking capability. The switching speed is then lost in the inverter application in comparison with unipolar devices, such as Si MOSFET. It is expected that GaN HFET and SiC MOSFET will replace SI MOSFET and Si IGBT respectively. Also, SiC IGBT is competing with its Si counterpart [28].

5.1 Diodes

Power diodes are usually used as rectifiers of AC currents, converters in the DC to AC inverters and as a protection of components. The free-wheeling (flyback) diodes are antiparallelly connected (see Figure 13) to active switches to enable a path for the inductive load current when switches turn-off.

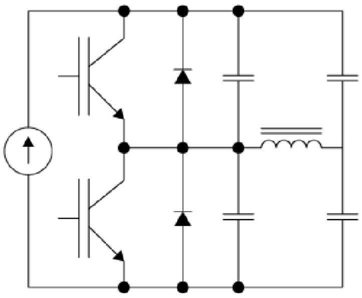

Figure 13: Series Resonant Half-bridge converter utilizing IGBTs with freewheeling diodes [29]

Whenever the switch turns-on, the freewheeling diodes turn from conductive to blocking state. In order to avoid induced voltage spikes and high-frequency oscillations, storage charges are to be depleted gently. The switching frequency range is between 1 kHz and the units of MHz in the lower power circuits. In high power circuits, this ranges from hundred Hz up to 1 kHz or more [30].

5.1.1 Antiparallel connected diodes

Integrated gate-commutated thyristor (IGCT) circuits widely utilize the discrete circular silicon diodes and the clamping diode. The latter is used to damp the voltage overshoots created by the di/dt. Good softness and high safe operating area (SOA) are vital. The neutral point and freewheeling diodes are necessary in more than 2-level inverters with low switching losses and ON-state, low leakage current and high SOA (di/dt 0.5-1.5kA/s) [30].

Figure 14 Typical appearance of ABB's Fast Recovery Diode [31].

The first developed fast recovery high-power diodes had issues with the oscillations during turn-off, the dynamic avalanche, the filamentation of current, etc. The discrete fast recovery high-power diodes are used in the IGCT circuit, owing to their very high power handling capability. The discrete diodes have an area that is 10-40 times higher than those in chip. Because of high SOA of the IGCTs, the diodes with high maximal current ratings and high active area have to be able to operate up to 140°C. However, with a higher diode area, certain problems with the electro-thermal stability and softness at reverse recovery occur. Diodes are expected to reliably operate at high DC voltages and with the currents of 5-6kA, which means enormous heating and current filamentation with fast turn-off. With the increasing area and the negative temperature coefficient of the V_f, the thermal stability is deteriorating [30]. Figure 14 shows a typical appearance of fast recovery diode offered by ABB.

5.1.2 Si Rectifier Diode

The blocking voltage of the SiC diode with the same drift layer thickness as in its Si counterpart can be 10x higher owing to the SiC large dielectric critical field. The high thermal conductivity also allows operating at higher current density ratings.

The classical Si PIN diodes have to deal with the reverse recovery process. When turning from conducting to blocking, the internal charge has to be removed, therefore the switching speed is slowed, excessive energy losses are generated and overvoltages or oscillations are created [30]. SiC Schottky diodes theoretically do not have to challenge this effect.

5.1.3 SiC Schottky Barrier Diode

Schottky Barrier Diode (SBD) can switch faster than a Si-pn junction diode. As a majority carrier device, SBD has no stored minority carriers which are injected into the device when ON and pulled when OFF [32]. SiC SBDs display extremely high switching speed and low on-states losses, but the disadvantages are lower blocking voltage and high leakage current. SiC SBDSs were commercialised in 2001 and since then their blocking voltage and conduction current ratings have continued to increase. However, commercially available are only 600, 650 and 1200V diodes with the currents of 2-40 A [33]. Cree also reported SiC Schottky diode with the blocking voltage of 1700V and current rating of 50A [34]. SiC SBDs parallel connected to IGBTs allowed the introduction of IGBT power modules, with SBDs as freewheeling diodes. The low reverse recovery charge in SiC SBDs compared to ultrafast Si PIN diodes makes these devices interesting for high switching speed applications.

5.1.4 SiC PIN Diode

Currently, SiC bipolar diodes are not commercialized because of reliability problems. However, SiC state-of-the-art P-I-N diode is reported, with 3.2V forward voltage drop at 180A and 4.5kV blocking voltage capability with the reverse leakage current of 1 μA [1]. Utilization of the SiC PIN diodes for the market is linked with the improvement of the semiconductor material quality, which causes their reliability obstacles.

5.1.5 GaN Power Rectifiers

The lack of electrically conducting GaN substrates is the reason why GaN Schottky power diodes are either of lateral or quasi-vertical topology. On sapphire substrates, the breakdown voltages of 9,7kV of lateral GaN rectifiers have been obtained. However, the forward voltage drop is still high. GaN rectifiers on Si or Sapphire are attractive for manufacturers due to the low cost. GaN SBDs are concurring with SiC counterparts in the lower power and frequency applications. Several papers regarding comparison of SiC and GaN SBDs have been published. [32] shows that 600V/2A GaN SBD is able to operate at high temperatures up to 175°C and at very high frequencies with low switching losses. However, the on-state voltages increase with temperature. Even though JBS GaN diodes are being researched, there are still some difficulties in the contact resistance to implanted P-type GaN [1].

5.2 Unipolar Power Switches

In terms of function as a switch, there are only two critical extreme states; the ON-state and the OFF-state. With regard to MOSFET, transistor should function as a perfect switch in OFF-state, hence blocking infinite voltage between the drain and the source with no leakage current, whereas in ON-state, transistor should provide no resistance to current flow between the drain and the source. The change between ON- and OFF-states should have no power loss and should be instant. However, ideal semiconductor switches are not real. Practical semiconductor switches are characterised by a breakdown voltage V_{BV}, on-state resistance R_{ON} and various parameters describing the losses incurred in each switching event. R_{ON} scales linearly with the surface area of power device, specific on-resistance R_{SP} is therefore normalized for description of the on-state performance [6] [35].

SiC power switches in the range of 600V are competing with Si power MOSFETs and Si IGBTs. These Si power switches benefit from their higher blocking voltages. However, in terms of 1.2-1.7 kV, these power devices are not considered. Si power MOSFET has large conduction losses while Si IGBT demonstrates high dynamic losses when fast switching [1].

5.2.1 SiC JFET

Particularly interesting for this voltage range is SiC JFET, with its ultralow specific on-resistance and ability to operate at high temperatures and high frequencies.

Infineon is offering a 1.2kV, 0.07 or 0.1-Ω on-resistance hybrid SiC JFET-based switch (see Figure 15) consisting of P-channel low-voltage Si MOSFET in series with a high-voltage N-type SiC JFET.

Figure 15: CoolSiC™ 1200V SiC JFET [36]

The JFET is in on-state at zero gate voltage. A negative gate voltage is necessary for change into the off-state. This is achieved by a cascade configuration with a low voltage MOSFET → LV off-state MOSFET pushes the source of JFET to positive potential relative to its gate and thus keeping the JFET in the off-state (see Figure 16) [36].

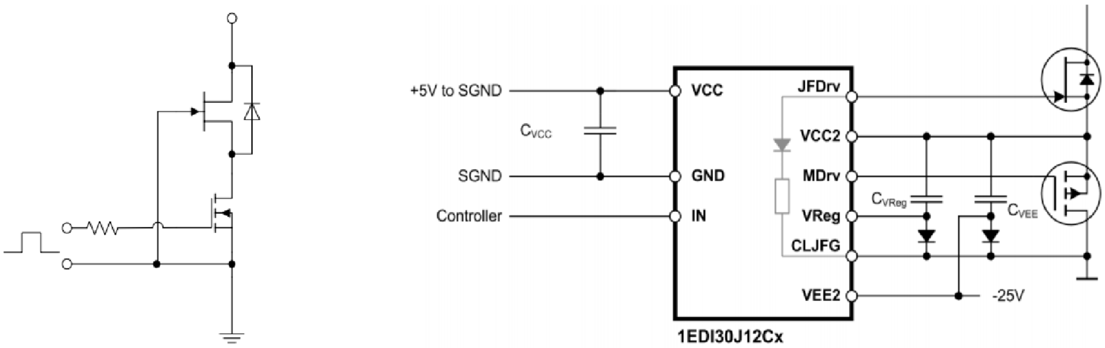

Figure 16: Cascade configuration and direct drive technology with 1EDI30J12Cx [36]

Using this configuration, the LV MOSFET is switched on and off with the JFET. This, however, presents two difficulties. Mostly, additional switching losses take place at turn-on due to the need of charging the output capacitances of the MOSFET. The second drawback is no direct control of the JFET, as a JFET Drain to LV MOS Gate capacitance is not present. Infineon presents the solution using the "direct drive" approach, where the JFET is switched-on and off with a negative gate voltage and 0V respectively. The series connected MOSFET is, on the other hand, always in on-state mode. The off-state is reached solely during start-up or in emergency case [36].

Target applications are solar, UPS and industrial drives. Unfortunately, because of the Si MOSFET in the package, high temperature operation for these devices is not possible [1][36].

5.2.2 SiC MOSFET

Owing to the emergence of SiC technology, lower on-state resistance of MOSFET is possible. Consequently devices with higher voltage and current characteristics are being manufactured. SiC MOSFET developments can be classified as low voltage and medium and high voltage devices. The former are represented by MOSFETs of 1.2kV, 1.7kV and 3.3kV blocking capability. These devices are used as alternative to Si IGBTs. The latter include MOSFETs with blocking voltage of 10kV, 15kV and higher. In terms of the power converters, SiC MOSFET can operate at higher switching frequencies considering lower switching losses when compared to Si IGBT. Furthermore, SiC MOSFET has a benefit of high temperature operation [37].

5.2.3 GaN HEMT

Due to the existence of 2DEG formed in AlGaN/GaN heterostructures of GaN power devices (high electron mobility values 1200-2000cm2/Vs), GaN HEMTs are normally-on devices because a negative bias must be applied to the gate for removing the 2DEG. GaN based devices are well-suited for high-power switching application due to a significant tradeoff between specific on-resistance and breakdown voltage. The high speed and low-loss switching performance makes these devices interesting for switching power supplies with ultrahigh bandwidth (in the MHz range) [1].

Power systems use preferably normally-off switches and since GaN HEMTs are intrinsically normally-on, some research has been made to develop normally-off GaN HEMTs structures [38]. Normally-on and off GaN HEMTs are commercially available with the breakdown voltage of 20-600 V.

5.3 Bipolar Power Switches

5.3.1 Phase Control Thyristors

PCT’s applications are focused on the GW range, such as in the transmission of power by line commutated ultra-high voltage direct current (UHVDC) systems. PCT in the existing UHVDC system has the blocking capability of 8.5kV with the maximal current rating of 4.2kA. Next to HDVC, PCTs are widely utilized in the industrial applications for traction, AC and DC drives, Static VAR Control (SVC), high current rectifiers, crowbar protections etc [30].

They are commercially available with the repetitive off-state and reverse voltages V_{DRM} and V_{RRM} up to 9kV and nominal ON-state current capability between 1 and 4kA.

5.3.2 Integrated Gate-commuted Thyristor

IGCTs provide impressive applications for the Medium Voltage Drivers (MVD) for industrial applications, such as Wind Power. Frequency converters with high power density and high reliability are essential in the area of Wind power, where the MVD technology contributed to the lower currents, lower system losses and finally to less space and less cabling. With the integrated turn-on/off drive unit, the IGCT can conduct like a thyristor and block dynamically and statically like a bipolar transistor [30].They are packaged as press-pack devices, with double side cooling and no wire bonding [39].

Asymmetrical IGCT offers a very good trade-off between the static and dynamic losses in the Voltage Source Inverters (VSI). Current Source Inverters and matrix converters utilize the IGCT with the reverse blocking capability, therefore the reverse blocking IGCTs are constructed as asymmetric with a free-wheeling diode in series or as a symmetric non-punch through device (SGCT) with the reverse blocking capability [30].

In terms of SiC, GTO structures have been reported, such as 4.5 kV, 120-A SiCGT (SiC Commutated Gate turn-off Thyristor) [1].

5.3.3 Si IGBT

IGBT belongs to the Bi-MOS design, which means that the device can be controlled via the MOS input contrary to the IGCT. IGBT have the advantage of inherent short circuit turn-off. The ON-state current of the internal transistor structure saturates with increasing collector voltage, which allows a safe turn-off of the IGBT, as long as it is done shortly after the short-circuit current is detected. Moreover, the di/dt can be controlled during the turn-on by adjusting the drive circuit RC constant, contrary to the IGCTs that are protected by extra parts against the excessive di/dt during uncontrolled turn-on.

Positive temperature coefficient of the Vcesat makes the paralleling of the IGBTs possible, therefore the possibility of usage in high-power modules. IGBTs are offered in the voltage ranges of 600 V up to 6.5kV with the current rating of hundreds A to kA [30].

IGBTs are usually encapsulated in the modules. However, ABB is also offering IGBTs in press-packs due to their advantages of easy electrical and mechanical series connection (see Figure 17) [39].

Figure 17: Typical appearance of ABB's IGBT press-pack [39]

The Si IGBTs require to be connected in series or using multi-level converter topologies for smart-grid power electronics at distribution levels. The former demands costly snubber circuits for voltage balancing and causes substantial power loss, while the latter requires complex controllers and has problems with balancing voltage and power [40].

As a result of these obstacles and emergence of SiC, there have been attempts to develop high voltage devices with the blocking capability up to 10kV. As it was mentioned before, 10kV 4h-SiC MOSFET's low on-resistance and high switching frequency capability are applicable in high voltage devices. However, similar to Si MOSFET, strong positive temperature coefficient together with increased drift resistance cause that these devices are not applicable for higher voltage and higher temperature operations [40].

IGBT's application fields are hybrid electric vehicles, traction systems, industrial motor drives, wind power and transmission and distribution of electric energy.

5.3.4 SiC IGBT

Due to its exceptional on-state performance, the SiC IGBT power switch is considered to have the most promising future potential for high-voltage applications. Several papers report the device with the blocking voltage capability over 10kV and it is likely that this voltage capability will be increased to 20-30kV in the future. Cree has successfully built 15kV 4h-SiC P-channel IGBT with the specific on-resistance of 24 mΩ·cm2 at room temperature with a gate bias of -20V. Low resistivity P-SiC substrates necessary for the N-channel IGBTs were obstacles, so originally IGBTs were created with a P-type drift [40]. However, with a technology progress of SiC, N-channel 4H-SiC IGBT is also reported by Cree with a blocking voltage of 12.5 kV and a room temperature differential specific on-resistance of 5.3 $m\Omega \cdot cm^2$ with a gate bias of 20V. [1]

6 Survey of Power Semiconductor Devices

6.1 Si Diode Presspacks

Manufacturer	**Configuration**	**Type**	V_{RRM}	I_{FSM}	I_{FAVM} /T_C	**Package**
ABB	5SDF 10H6004	GTO Freewheeling Diode	6000 V	18 kA	1 100 A/ 85°C	94mm/63mm
ABB	5SDD 31K6000	Normal Recovery diodes	6000 V	40 kA	3052 A/ 85°C	101.5mm/63mm
ABB	5SDF 0131Z0401	High Frequency Welding Diode	400 V	70 kA	13 058A/ 85 °C	63.5mm/57mm
Dynex	DRD560G90	Rectifier Diode	9000 V	10 kA	557 A/ 75°C	58mm/26.5mm
Dynex	DSF11060SG	Fast Recovery Diode	6000 V	4,2 kA	400 A/ 65°C	58.5mm/25.4mm
Infineon	D901S45T	Fast Rectifier Diode	4500 V	21.5 kA	900 A/ 80°C	100mm/26mm
Infineon	D1461S45T	GTO Freewheeling Diode	4500 V	28 kA	1460A/ 85°C	100mm/26mm
Infineon	65DN06	Welding Diode	600 V	95 kA	8470 A/ 98°C	65mm/5mm

Table 2: Si Diode Presspacks [41] [42] [43]

6.2 Si Thyristor / Diode Modules

Manufacturer	**Product**	V_{RRM} /V_{DRM}	I_{FSM} /I_{TSM}	**I_{FAVM} / T_C / I_{TAVM} / T_C**	**Configuration**
Infineon	DZ950N44K	4400 V	29 kA	950/100 (180° el sin) A/°C	Single Switch
Infineon	DZ1100N22K	2200 V	48 kA	1100/100 (180° el sin) A/°C	Single Switch
Semikron	SKKE 1200	2200 V	40 kA	1180/100 (180° el sin) A/°C	Single Switch
Semikron	SKKQ 1500	1800 V	40 kA	1500/150 (180° el sin) A/°C	2 Switches

Table 3: Thyristor/Diode Modules [43] [44]]

6.3 Si Phase Controlled Thyristor

Manufacturer	**Product**	V_{DRM} / V_{RRM}	I_{TSM}	I_{TAV}	**Package**
ABB	5STP 37Y8500	8000 V	90 kA	3660 A	192mm/138mm
ABB	5STP 52U5200	5200 V	99 kA	5060	172mm/110mm
Dynex	DCR2560A85	8500 V	32,5 kA	2560 A	148mm/35mm
Dynex	DCR7610H28	2800 V	105 kA	7610 A	172mm/35mm
Infineon	T600N95TOH PR	9500 V	12,8 kA	590 A	75mm/26mm
Infineon	T4003N52TOH PR	5200 V	100 kA	3400 A	172mm/86mm

Table 4: Phase Controlled Thyristor [41] [42] [43]

6.4 Si IGBT Modules

Manufacturer	Product	V_{CES}	I_C	Configuration
ABB	5SNA 3600E170300	1700 V	3600 A	Single Switch
ABB	5SNA 0750G650300	6500 V	750 A	Single Switch
ABB	5SNG 0150P450300	4500 V	2 x 150 A	Half Bridge
Dynex	DIM2400ESM17-A	1700 V	2400 A	Single Switch
Dynex	DIM750ASM65-TS	6500 V	750 A	Single Switch
Dynex	DIM400XCM45-TS001	4500 V	400 A	Chopper
Infineon	FZ3600R17HE4	1700 V	3600 A	Single Switch
Infineon	FZ1200R45HL3	4500 V	1200 A	Single Switch
Infineon	FS500R17OE4D	1700 V	500 A	Sixpack
Semikron	SKM900GA12E4	1200 V	900 A	Single Switch
Semikron	SKM600GA17E4	1700 V	600 A	Single Switch
Semikron	SK 15 DGDL 126 ET	1200 V	15 A	Seven Pack

Table 5: IGBT Modules [41] [42] [43] [44]

6.5 Press pack IGBT and diode modules

Manufacturer	Product	V_{CES}	I_C	V_{CESAT}	V_F
ABB	5SNR 20H2501	2500 V	2000 A	2.7 V	1.9 V
ABB	5SNA 3000K452300	4500 V	3000 A	3.65 V	3.0 V

Table 6: Press pack IGBT modules [41]

6.6 Asymmetric and reverse conducting IGCTs

Manufacturer	Product	V_{DRM}	V_{DC}	I_{TGQM}	I_{TAVM}	Package
ABB	5SHY 35L4520	4500 V	2800 V	4000 A	1700 A	85mm/26mm
ABB	5SHY 55L4500	4500 V	2800 V	5000 A	1870 A	85mm/26mm
ABB	5SHY 42L6500	6500 V	4000 V	3800 A	1290 A	85mm/26mm

Table 7: Asymmetric IGCTs [41]

Manufacturer	Product	V_{DRM}	V_{DC}	I_{TGQM}	I_{TAVM}/I_{FAVM}	Package
ABB	5SHX 26L4520	4500 V	2800 V	2200 A	1010 A	85mm/26mm
	Diode part				390 A	
ABB	5SHX 19L6020	5500 V	3300 V	1800 A	840 A	85mm/26mm
	Diode part				340 A	

Table 8: Reverse conducting IGCTs [41]

6.7 Reverse blocking IGCT

Manufacturer	**Product**	V_{DRM}	V_T	I_{TGQM}	I_{TAVM}/I_{FAVM}	**Package**
ABB	5SHZ 11H6500	6500 V	5.87 V	1100 A	490 A	62.8/13.8

Table 9: Reverse blocking IGCT [41]

6.8 SiC Schottky Diodes

Manufacturer	**Product**	V_{RRM}	I_F	Q_C	$T_{j,max}$
Infineon	IDW40G120C5B	1200 V	20 /40 A	101 /202 nC	175°C
Infineon	IDW20G65C5	650 V	20 A	29 nC	175°C

Table 10: SiC Schottky Diodes [43]

6.9 SiC JFET

Manufacturer	**Product**	V_{DS}	$R_{DS\ (on)}$	I_D	P_{tot}	I_{Dpuls}
Infineon	IJW120R100T1	1200 V	0.1 mΩ	26 A	190 W	78 A
Infineon	IJW120R070T1	1200 V	0.07 mΩ	35 A	238 W	114 A

Table 11: SiC JFET [43]

6.10 SiC MOSFET modules

Manufacturer	**Product**	V_{DS}	I_D	**Configuration**
Semikron	SKiiP 13ACM12V17	1200 V	24 A	Sixpack
Semikron	SKM500MB120SC	1200 V	541 A	Half Bridge
Semikron	SK45MLET12SCp	1200 V	41 A	Single Switch

Table 12: SiC MOSFET modules [44]

6.11 Hybrid SiC Power Modules (IGBTs and SiC Diodes)

Manufacturer	**Product**	V_{CES}	I_C	**Configuration**
Infineon	FF600R12IS4F	1200 V	600 A	Dual
Infineon	DF200R12W1H3F_B11	1200 V	200 A	Chopper
Infineon	F4-75R07W2H3_B51	650 V	75 A	Fourpack
Semikron	SKiiP25AC12F4V19	1200 V	50 A	Sixpack
Semikron	SKM200GB12F4SiC2	1200 V	200 A	Half Bridge
Semikron	SEMiX603GB12E4SiCp	1200 V	600 A	Half Bridge

Table 13: Hybrid SiC Power Modules [43] [44]

6.12 GaN HEMTs

Manufacturer	Product	Frequency band Min	 Max	P_{1dB}	Supply Voltage
Infineon	GTVA220701FA V1 R2	1805.0 MHz	2170.0 MHz	70.0 W	50 V
Infineon	GTVA261701FA V1 R2	2620.0 MHz	2690.0 MHz	170.0 W	50 V

Table 14: GaN HEMTs [43]

Conclusion

The main four manufacturers of power semiconductor technology on European market are Swedish-Swiss ABB, Dynex Semicondoctor based in England, German Infineon and independent Semikron.

ABB, Dynex and Infineon are also making presspacks containing diodes of different voltage range and of different type (freewheeling diodes, standard and fast recovery diodes, welding diodes). Voltage range of diodes offered by Infineon is between 200V to 6000V with the current handling capabilities of 56A to 8400A. ABB offers a similar range. However, Dynex has in the portfolio rectifier diodes with the voltage range up to 9000 V (see Table 2) in the portfolio.

All four companies are selling Si IGBT modules. ABB is moreover offering presspacks in contrast with the traditional modules, as it was mentioned in the fifth chapter. They use different configurations: single switch, half bridge, chopper, six pack or seven pack). The voltage ranges from 1,7kv to 4,5kV, with ABB and Dynex offering 6.5kV modules.

As mentioned above, some WBG based devices are already competing with their silicon counterparts. SiC Schottky diodes are offered by German semiconductor manufacturer Infineon. Infineon has also expanded their SiC portfolio on JFET and hybrid SiC modules. Semikron is offering both hybrid and full SiC power modules.

Semikron's hybrid power modules utilize IGBT chips with SiC Schottky freewheeling diodes (see Table 13), while full SiC power modules of Infineon and Semikron combine SiC MOSFET and SiC Schottky diodes, as it is presented in Table 12. Unfortunately, these are the sole sellers of the WBG devices in Europe.

The aim of the work was to review the currently modern high power semiconductor devices. The emergence of the wide-band gap semiconductor materials could not have been overlooked as SiC and GaN materials demonstrate the future of power electronics sector. Numerous papers also prove the continuous research and development of devices based on these materials. However, it is safe to assume that silicon will dominate the market in the next decade; considering that it took 60 years of development to get the material to its current position in the semiconductor industry. So despite the rapid progress, SiC and GaN technologies are still immature compared to the Si.

References

[1] MILAN, José et al. *A Survey of Wide Bandgap Power Semiconductor Devices*. In: *Power Electronics, IEEE Transactions on* [online]. May 2014, Vol. 29, 5, pp. 2155-2163 [cit. 2016-5-22]. DOI: 10.1109/TPEL.2013.2268900. Available at: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6532359&isnumber=6709815

[2] KAMINSKI, Nando. *State of the art and the future of wide band-gap devices.* In: *2009. EPE '09. 13th European Conference on Power Electronics and Applications* [online]. Barcelona: IEEE, 2009, pp. 1-9 [cit. 2016-5-22]. Available at: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=5279082&isnumber=5278662

[3] OZPINECI, Burák and TOLBERT, Leon. *Comparison of wide-bandgap semiconductors for power electronics applications* [online]. Oak Ridge, Tennessee : Oak Ridge National Laboratory, 12 December 2003 [cit. 2016-5-22]. Available at: http://web.ornl.gov/~webworks/cppr/y2001/rpt/118817.pdf

[4] GRUMMEL, Brian**.** *Design and characterization of high-temperature packaging* [online]. Orlando, Florida : University of Central Florida, College of Engineering and Computer Science, Department of Electrical Engineering and Computer Science, 2012. PhD. Thesis, pp. 12-14 [Cit. 2016-5-22]. Available at: http://etd.fcla.edu/CF/CFE0004499/Grummel_Brian_J_201212_PhD.pdf

[5] SHARMA, Ashutosh et al. *SiC based Technology for High Power Electronics and Packaging Applications*. In: *Journal of the Microelectronics & Packaging Society*, 2014 [online]. Vol. 21, pp. 1-8 [cit. 2016-5-22]. Available at: https://www.researchgate.net/publication/265144510_SiC_based_Technology_for_High_Power_Electronics_and_Packaging_Applications

[6] SZE, S. M. and KWOK, K. Ng. *Physics of semiconductor devices.* Hoboken : John Wiley & Sons, Incl., 2007, pp. 549. ISBN: 13: 978-0-471-14323-9.

[7] *Wikipedia: Metalorganic vapour phase epitaxy* [online]. [Cit. 2016-5-22]. Available at: https://en.wikipedia.org/wiki/Metalorganic_vapour_phase_epitaxy

[8] RUNTON, David W. *History of GaN: High-Power RF Gallium Nitride (GaN) from Infancy to Manufacturable Process and Beyond*. In: *Microwave Magazine* [online]. IEEE. Vol. 14, 3, pp. 82-93 [Cit. 2016-5-22].

DOI: 10.1109/MMM.2013.2240853 Available at: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6492190

[9] KAZUKIYO, Joshin. *Outlook for GaN HEMT Technology.* In: *Fujitsu scientific & technical journal* [online]. January 2014, Vol. 50, pp. 138-143 [cit. 2016-5-22]. Available at: http://www.fujitsu.com/global/documents/about/resources/publications/fstj/archives/vol50-1/paper21.pdf

[10] *GaN Based Power Devices: Cost Effective Revolutionary Performance.* In: *Power Electronics Europe* [online]. 2008**.** [cit. 2016-5-22] Available at: http://www.irf.com/pressroom/articles/560pee0811.pdf

[11] BOYLESTAD R. L. and NASHELSKY L. *Electronic Devices and Circuit Theory*. New Jersey: Pearson, 2013. pp. 10-13, 811-812. ISBN: 978-0-13-262226-4.

[12] BALIGA, B. Jayant. *Fundamentals of Power Semiconductor Devices.* Raleigh: North Carolina State University, 2008. pp. 1-3, 279-285, 629-630, 742 [cit. 2016-5-22]. ISBN 978-0-387-47314-7.

[13] PERRET, Robert, [ed.]. *Power Electronic Semiconductor Devices.* ISTE Ltd, 2009. pp. 442-444, 446-448 [cit. 2016-5-22]. ISBN: 978-1-84821-064-6

[14] BOUŠEK, Jaroslav and HORÁK Michal. *Electronic Devices.* Brno: Faculty of Electrical Engineering and Communication of University of Technology in Brno, 2006. pp. 120-121 [cit. 2016-5-22]. Available at: https://www.vutbr.cz/studis/student.phtml?gm=gm_detail_predmetu&apid=134667

[15] SCHWIERZ, F. and Juin J. Liou. *Modern Microwave Transistors.* Hoboken : John Wiley & Sons, Inc., 2003. pp. 140-141 [cit. 2016-5-22]. ISBN: 0-471-41778-5

[16] *Wikipedia: Band diagram of GaAs/AlGaAs heterojunction-based HEMT, at equilibrium* [online]. [Cit. 2016-5-22]. Available at: https://en.wikipedia.org/wiki/High-electron-mobility_transistor#/media/File:HEMT-band_structure_scheme-en.svg

[17] *Heat Dissipation*. In: *Thermal Management* [online]. pp. 567-570 [cit. 2016-5-22]. Available at: http://www.nxp.com/documents/application_note/APPCHP7.pdf

[18] PICKERT, V. et al. *An experimental and computational study of water cooled heatsinks for HEV's.* In*: 5th IET International Conference on Power Electronics, Machines and Drives (PEMD 2010)* [online]. Brighton, UK: IET. 2010, pp. 1-6 [cit. 2016-5-18]. Available at:

http://ieeexplore.ieee.org/xpl/login.jsp?tp=&arnumber=5522477&url=http%3A%2F%2Fieeexplore.ieee.org%2Fxpls%2Fabs_all.jsp%3Farnumber%3D5522477

[19] MADHUSOODHANAN, S. et al. *Thermal design considerations for medium voltage power converters with 15 kV SiC IGBTs.* In : *6th International Symposium on Power Electronics for Distributed Generation Systems (PEDG)* [online]. Aachen : IEEE, 2015, pp. 1-8 [cit. 2015-5-18]. Available at: http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=7223105

[20] SIKORSKI, Wojciech and ZIOMEK, Waldemar. *Detection, Recognition and Location of Partial Discharge Sources Using Acoustic Emission Method* [online]. InTech. pp. 49 [cit. 2015-5-18]. DOI: 10.5772/31394. Available from: http://www.intechopen.com/books/acoustic-emission/detection-recognition-and-location-of-partial-discharge-sources-using-acoustic-emission-method

[21] ROMANO, P et al**.** *Partial discharges on IGBT modules: Are sinusoidal waveforms sufficient to evaluate behavior?*. In: *2014 IEEE Conference on Electrical Insulation and Dielectric Phenomena (CEIDP)* [online]. Des Moines, IA: IEEE 2014, pp. 224 [cit. 2015-5-18]. DOI: 10.1109/CEIDP.2014.6995815. Available at: http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=6995815&tag=1

[22] RAHIMO, M. *Ultra high voltage semiconductor power devices for grid applications.* In: *2010 IEEE International Electron Devices Meeting (IEDM).* San Francisco: IEEE, 2010, pp. 13.4.1 - 13.4.4 [cit. 2015-5-18]. DOI: 10.1109/IEDM.2010.5703355 Available at: http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=5703355

[23] STRASS, Achim. *Power semiconductor and packaging trends in vehicle.* In: *International Electric Vehicle Symposium and Exhibition*. Seoul : Infineon Technologies Korea, 2015, pp. 1-4 [cit. 2015-5-18]. Available at: http://www.evs28.org/event_file/event_file/1/pfile/EVS28_PackgeTrends_v2.pdf

[24] SHEN, Z. John. *Power Semiconductor Devices for Hybrid, Electric, and Fuel Cell Vehicles*. In: *Proceedings of the IEEE* [online]. IEEE, 2007, pp. 778 – 789 [cit. 2016-5-22]. DOI: 10.1109/JPROC.2006.890118. Available at: http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=4168030

[25] LEE, K. k. *Advances in the application of power electronics to railway traction.* In: *2015 6th International Conference on Power Electronics Systems and Applications (PESA)* [online]. Hong Kong : IEEE, 2015. pp. 1-4 [cit. 2016-5-22].

DOI: 10.1109/PESA.2015.7398960. Available at: http://ieeexplore.ieee.org/xpl/articleDetails.jsp?tp=&arnumber=7398960

[26] LADOUX P. et al**.** *Outlook for SiC devices in traction converters*. In: *Electrical Systems for Aircraft, Railway and Ship Propulsion (ESARS)* [online]. Bologna : IEEE, 2012 [cit. 2016-5-22]. DOI: 10.1109/ESARS.2012.6387463. Available at: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6387463&isnumber=6387375

[27] BRENNA, Moriss. *Application Prospective of Silicon Carbide (SiC) in railway vehicles.* In*: AEIT Annual Conference - From Research to Industry: The Need for a More Effective Technology Transfer (AEIT)* [online]. Trieste : IEEE, 2014 [Cit. 2016-5-22]. DOI: 10.1109/AEIT.2014.7002062. Available at: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=7002062&isnumber=7002006

[28] OKUMURA, H. *Power electronics innovation by Silicon Carbide power semiconductor devices.* In: *2014 IEEE International Meeting for Future of Electron Devices, Kansai (IMFEDK)* [online]. Kyoto: IEEE, 2014 pp. 1-2 [Cit. 2016-5-22] DOI: 10.1109/IMFEDK.2014.6867086. Available at: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6867086&isnumber=6867036

[29] *Infineon: Topology Fundamentals and Their Basis Waveforms* [online] Infineon Technologies AG, © 1999 – 2016 [Cit. 2016-5-22]. Available at http://www.irf.com/product-info/igbt/switching.pdf.

[30] VOBECKY, Jan. *Design and Technology of High-Power Silicon Devices.* In: *Mixed Design of Integrated Circuits and Systems (MIXDES), 2011 Proceedings of the 18th International Conference* [online]. Gliwice: IEEE, 2011, pp. 17-22 [cit. 2016-5-22]. Available at: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6016023

[31] *ABB: Fast Recovery Diodes* [online] ABB, © Copyright 2016 [Cit. 2016-22-5]. Available at: http://new.abb.com/semiconductors/Diodes/fast-recovery-diodes

[32] BADAWI Nasser et al. *Evaluation of 600V GaN and SiC Schottky diodes at different temperatures.* In: *2013 15th European Conference on Power Electronics and Applications (EPE)* [online]. Lille: IEEE, 2013, pp. 1-7. [Cit. 2016-5-22]. DOI: 10.1109/EPE.2013.6634641 Available at:

http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6634641&isnumber=6631728

[33] *Infineon: Silicon Carbide (SiC)* [online]. Infineon Technologies AG, © 1999 - 2016 [cit. 2016-5-22]. Available at: http://www.infineon.com/cms/en/product/power/sicarbide-sic/channel.html?channel=ff80808112ab681d0112ab6a50b304a0

[34] *Wolfspeed: SiC Schottky Diodes* [online]. Cree, Inc. Copyright © 2016 [cit. 2016-5-22]. Available at: http://www.wolfspeed.com/power/products/sic-schottky-diodes/table

[35] DISNEY, D.et al. *Review of Silicon Power Semiconductor Technologies for Power Supply on Chip and Power Supply in Package Applications.* In: *IEEE Transactions on Power Electronics* [online]. Vol. 28, no. 9, pp. 4168 - 4169 [Cit. 2015-12-10]. DOI: 10.1109/TPEL.2013.2242095 Available at: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6463482&isnumber=6463474

[36] *Infineon: SiC- JFET Silicon Carbide- Junction Field Effect Transistor.* [Cit. 2016-5.22]. Available at: http://www.infineon.com/dgdl/Infineon-IJW120R100T1-DS-v02_00-en.pdf?fileId=db3a304341e0aed001420353f03a0e4b

[37] *HAZRA. S.* et al. *High Switching Performance of 1700-V, 50-A SiC Power MOSFET Over Si IGBT/BiMOSFET for Advanced Power Conversion Applications*. In: IEEE Transactions on Power Electronics 2015, Vol. 31 pp. 1 [cit. 2016-5-22]. DOI: 10.1109/TPEL.2015.2432012. Available at: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=7105923&isnumber=7394209

[38] HUOLIN, Huang, et al. *Design of novel normally-off AlGaN/GaN HEMTs with combined gate recess and floating charge structures.* In: *2013 IEEE 10th International Conference on Power Electronics and Drive Systems (PEDS)* [online]. Kitakyushu: IEEE, 2013. pp. 555-558 [cit. 2015-22-10]. DOI: 10.1109/PEDS.2013.6527081. Available at: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6527081&isnumber=6526975

[39] *ABB: Press-pack IGBT and diode modules* [online]. ABB, © Copyright 2016 [cit. 2016-5-22]. Available at: http://new.abb.com/semiconductors/stakpak

[40] KADAVELUGU, A. *Characterization of 15 kV SiC n-IGBT and its application considerations for high power converters.* In: *2013 IEEE Energy Conversion Congress and Exposition*. Denver: IEEE, 2013, pp 2528-2535 [cit. 2016-5-22]. DOI: 10.1109/ECCE.2013.6647027. Available at: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6647027&isnumber=6646663

[41] *ABB: Semiconductors* [online]. ABB, © Copyright 2016 [cit. 2016-5-22]. Available at: http://new.abb.com/semiconductors

[42] *Dynex: Power semiconductors* [online]. Dynex Semiconductor © 2016 [cit. 2016-5-22]. Available at: http://www.dynexsemi.com/dynex-power-semiconductors

[43] *Infineon: Power* [online]. Infineon Technologies AG © 1999 – 2016. [cit. 2016-5-22]. Available at: http://www.infineon.com/cms/en/product/power/channel.html?channel=db3a304319c6f18c011a154646852706

[44] *Semikron: Products* [online]. SEMIKRON © 2016 [cit. 2016-5-22]. Available at: http://www.semikron.com