THE CURRENT STATUS OF POWER SEMICONDUCTORS

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Abstract. *Trends in the design and technology of power semiconductor devices are discussed on the threshold of the year 2015. Well established silicon technologies continue to occupy most of applications thanks to the maturity of switches like MOSFET, IGBT, IGCT and PCT. Silicon carbide (SiC) and gallium nitride (GaN) are striving to take over that of the silicon. The most relevant SiC device is the MPS (JBS) diode, followed by MOSFET and JFET. GaN devices are represented by lateral HEMT. While the long term reliability of silicon devices is well trusted, the SiC MOSFETs and GaN HEMTs are struggling to achieve a similar confidence. Two order higher cost of SiC equivalent functional performance at device level limits their application to specific cases, but their number is growing. Next five years will therefore see the co-existence of these technologies. Silicon will continue to occupy most of applications and dominate the high-power sector. The wide bandgap devices will expand mainly in the 600 - 1200 V range and dominate the research regardless of the voltage class.*

Key words: *power devices, silicon, silicon carbide, gallium nitride, thyristor, transistor.*

1. INTRODUCTION

There is no doubt that power semiconductor devices play an important role in the development of modern society. They are the key components of an ever increasing number of applications which process the electrical power ranging from units of watts to gigawatts with modulation frequency of hertz to gigahertz. After sixty five years of development we reached the stage where different semiconductor materials compete for their use. Silicon is defending its dominance by ongoing improvements in ratings (up to 10 kA), cost reduction (using up to 12" wafers) and circuit topologies. Wide bandgap semiconductors like SiC and GaN strive to profit from their much better electrical strength and thermal conductivity in order to compensate for their much higher cost. Old favourite arguments are the profit at a system level due to a higher operation frequency and lower equipment volume. Typical arguments against the wide bandgap devices are missing experience with their gate dielectric reliability, about two orders higher cost and low current ratings (≤ 50 A). At the moment, $\approx 1 - 2$ \$/A of output current of a 1200 V/100 A SiC inverter against ≈ 0.02 \$/A for that of Si can be compensated only in few cases. This is

when several superior features are fulfilled at the same time, like very high frequency (high power density), the highest possible conversion efficiency and the existence of low loss body diode (solar inverters, UPS). The rest is in principal not acceptable for customers due to the high prices. These facts motivate researchers, designers and managers to change this situation. In the following paragraphs a short summary is given on the current status and possible future trends in power devices. For this purpose a classical sorting of components into groups according to electrical power is used as shown in Fig. 1.
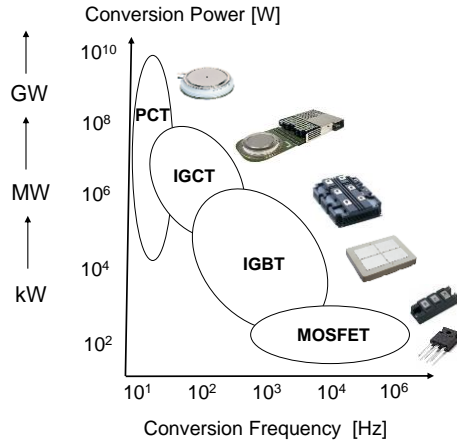

Fig. 1 Power semiconductor devices
PCT = Phase Controlled Thyristor,
IGCT = Integrated Gate Commutated Thyristor,
IGBT = Integrated Gate Bipolar Transistor,
MOSFET = Metal Oxide Semiconductor Field Effect Transistor

2. MOSFET

Since about forty five years has been the silicon MOSFET the power device of choice for breakdown voltages below 1000 V. For discrete parts, this is (1) thanks to the invention of the vertical double-diffused MOSFET structure (VDMOS) in favor of simple processing [1], (2) trench VDMOS with higher cell density bringing lower conduction losses, and (3) charge compensation principle (super-junction) for low drift layer resistance breaking the original silicon limit of specific on-state resistance vs. breakdown voltage [2].
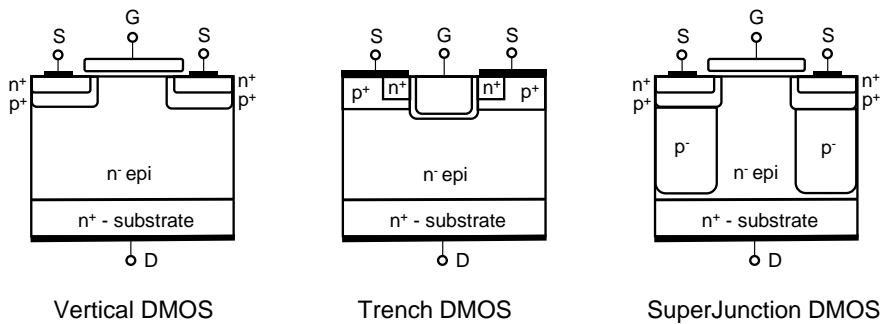

Fig. 2 Vertical double-diffused MOSFET design concepts

The invention of lateral DMOS (LDMOS) and reduced surface field (RESURF) [3] concepts have allowed the integration with bipolar and CMOS devices into the Bipolar CMOS DMOS (BCD) [4], Smart Power [5] and other platforms. From the application viewpoint, the existence of internal body diode makes the power MOSFET concept very practical.
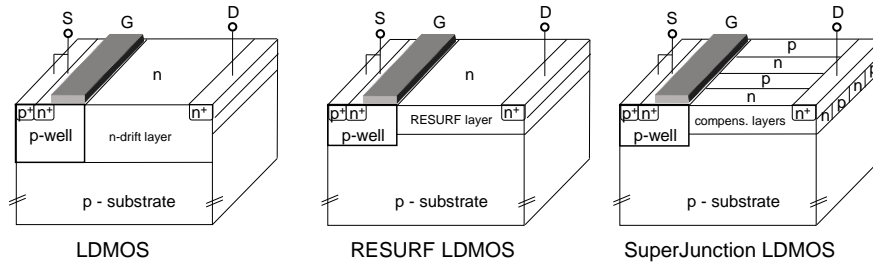

Fig. 3 Lateral double-diffused MOSFET design concepts

Since about 2010, the silicon MOSFET is facing competition from the SiC MOSFET. Because of the low inversion channel mobility leading to a high channel resistance, the SiC MOSFETs are typically available from breakdown voltage of 900 V. Their specific on-state resistance R_{ON_SP} is claimed to approach the theoretical value for the SiC 1-D unipolar device starting from the breakdown voltages of 3.3 kV [6]. For 900 V voltage class they outperform the best in class silicon device, which is for example the latest generation of CoolMOS [7]. While $R_{ON\_SP} \approx 10 \text{ m}\Omega.\text{cm}^2$ for the 650 V superjunction MOSFET, it is $R_{ON\_SP} \approx 2.3 \text{ m}\Omega.\text{cm}^2$ for the next generation 900 and 1200 V SiC MOSFETs. By factor of five lower R_{ON_SP} of the SiC switches is nowadays a typical benchmarking figure. In addition, the SiC devices offer significantly lower temperature dependence of R_{ON_SP} and very low charge of output capacitance Q_{oss}, while the silicon MOSFETs go in the opposite direction due to the reduction of a cell pitch. In specific applications, this could be a valid argument for compensation of a much higher price for the SiC die by making profit at the system level, especially in the range 900 – 1200 V, which is free of competition [7]. But the producers of SiC devices like Cree are aiming much higher. They offer their MOSFETS up to 15 kV and demonstrate bipolar devices up to 27 kV. They are seeking new applications to oust the producers of silicon devices from their traditional markets. Typical problems, like high price, missing experience with reliability (e.g. gate oxide and V_{th} stability), and low current ratings, are still to be overcome.

Another competition for the 650 V superjunction MOSFET in the future is the GaN HEMT [7]. To be cost competitive, the mainstream HEMT is produced by epitaxial growth on a silicon wafer. Consequently, it is (1) a lateral device, (2) it has a high defect density at the epitaxial layer, which allows us to apply only a much lower dc link voltage compared to the breakdown voltage, and (3) it has a relatively low thermal conductivity and capacity. The attractiveness of this concept lies in very low switching and on-state losses. However, the latter grows much more with increasing temperature than that of the SiC MOSFET.

To overcome the inherent limitations of the lateral GaN devices, the *ARPA-E SWITCHES Program* has been launched in 2014 [8]. The goal is to develop a 1200 V / 100 A single die vertical GaN switch, which would have the potential to achieve the target cost of 0.1 $/A. This

value is claimed to be at cost parity with the silicon switch. However, one should treat it with caution, because it is deduced from the distributor prices. The current cost of a typical silicon foundry is at least five times lower and it can drop further with increasing the size of the starting silicon wafer towards 300 mm. Nevertheless, such ambitious programs are needed to boost the GaN technology.

Benefiting from CMOS technology advancements, the unipolar transistor has become the most developed power device technology. There is no reason for being it otherwise in the future. In addition to the classical planar and trench gate architectures mentioned above, there has already been demonstrated nanoscale device concepts, e.g. FinFET 3D approach on GaN substrate [9], Gate All Around (GAA) FET concept [10], etc. Moreover, there is not only silicon, SiC and GaN. Since recently, diamond substrates are available with p-type boron doped and n-type phosphorus doped epitaxial layers. Possibilities for an attractive research are further growing.

3. IGBT

At the beginning of 1980s´, the on-state resistance of silicon unipolar devices has been found too high above the breakdown voltage of 600 V. This stimulated the invention of a MOS-controlled power device with a carrier injection from the side opposite to that of the MOS control. The original designation *Power MOSFET with an Anode Region* [11], *The Insulated Gate Rectifier (IGR)* [12] or *Conductivity Modulated FET* (*COMFET*) [13] unified later in the term *Insulated Gate Bipolar Transistor* (*IGBT*). Nowadays, the IGBT is the device of choice for the voltage classes ranging from 650 V to 6.5 kV. The main reasons are (1) the superior cost relative to other technologies, (2) the process-adjustable position at the trade-off curve between the on-state ($V_{ce\,sat}$) and switching losses E_{off}, (3) high current ratings of power modules in the range of switching frequencies relevant for the most of kW, MW, and up to 1 GW applications, (4) possibility to integrate the free-wheeling diode (FWD) at the same chip (RC-IGBT, BiGT, RCDC) or to optimize the FWD independent of the IGBT, (5) short circuit withstanding capability, (6) low temperature dependence of the on-state losses.

(1) The production of IGBT chips requires a similar technology as that of the MOSFET. One more process is the anode implantation at the backside. The field-stop (soft-punch through) n-type buffer layer of the state-of-the-art IGBTs can be for the voltage classes of ≥ 2.5 kV pre-diffused already at the starting silicon. Only for the low voltage IGBTs (≤ 1700 V), a more demanding thin wafer technology is needed. In this case, the wafer is usually thinned by grinding and spin etching after completion of the MOS part and then implanted for the n-type buffer and p-type anode. The record low wafer thickness at 100 μm for 1200 V class has been achieved, for example using the thin proton implanted buffer layer instead of the thicker pre-diffused one [14]. There are also further processing options for the thin wafer processing.

(2) The possibility to adjust the buffer and anode doping profiles at the same time provides a great flexibility in controlling the bipolar gain of the IGBT. This reflects at the position at the trade-off curve between the $V_{ce\,sat}$ and E_{off}, at the magnitude of leakage current (T_{jmax}), short circuit withstanding capability, etc. The devices with low E_{off} (higher $V_{ce\,sat}$) can be operated at higher frequencies and alternatively with the SiC

FWDs. The devices with low $V_{ce\,sat}$ (higher E_{off}) are preferred in the low-frequency applications, like for example in the multilevel converters for energy transmission and distribution. Again, the adjustment of buffer and anode doping is more demanding at the low voltage IGBTs, because it can be efficiently processed only after the wafer thinning with finished MOS part including the passivation of junction termination. For fast IGBTs the limited temperature for the activation of p-type anode using a classical furnace is not a problem. For the IGBTs with low $V_{ce\,sat}$, the laser annealing technology is available, which exposes only a thin anode surface layer into the melting regime for the limited period of time, typically between 100 and 200 ns, while the cathode stays at a safely low temperature [15].
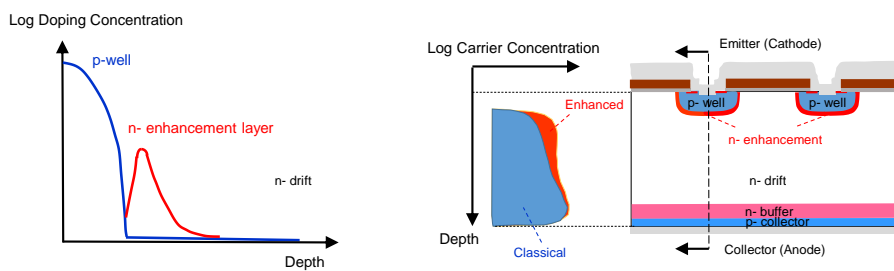

Fig. 4 Plasma enhancement at cathode side of the state-of-the-art IGBT

(3) The original invention of the IGBT concept with the injection of holes from the anode side significantly lowered the $V_{ce\,sat}$ and increased power density. The enhancement of the electron-hole plasma at the cathode side for further reduction of the on-state losses of IGBT modules belongs to the achievement of the last decade. The planar and trench soft punch-through (field-stop) IGBTs have developed into the enhanced trench [16] and enhanced planar IGBTs [17] with sophisticated shaping of the on-state plasma (see Fig.4). The enhanced trench IGBT represents the most important design concept for the two chip, i.e. IGBT and diode, solution. For example, it moved recently the maximal ratings of the 6.5 kV IGBT module to 1 kA [18]. In addition, the power density of the low voltage IGBT technology is expected to grow. By further reduction of the cell pitch, the maximal operating temperature of 1700 V modules is expected to achieve $T_{jmax} = 200\ ^{\circ}C$ around the year 2017 [7].

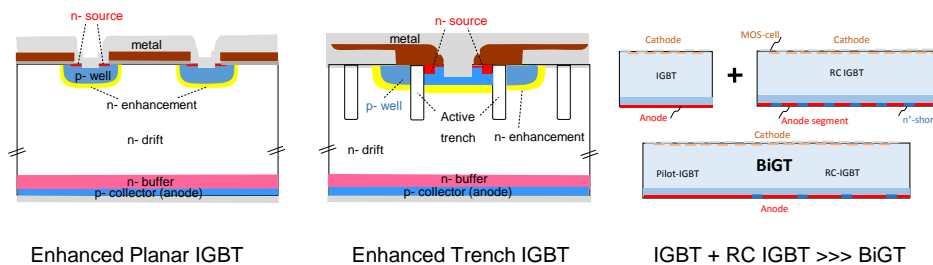Enhanced Planar IGBT   Enhanced Trench IGBT   IGBT + RC IGBT >>> BiGT

Fig. 5 State-of-the-art IGBT design concepts

(4) Another way of increasing the power density is the reverse conducting RC-IGBT concept, where both the IGBT and FWD are integrated at the same chip. The consequence of the fact that the IGBT and FWD share the same silicon is a bigger and more uniform current and thermal load of the chip as well. Consequently, the RC-IGBT chip is exposed to a much lower temperature swings (ΔT) during continuous operation, which increases the load cycling capability. In addition, the anode shorts, which form the cathode of the FWD, provide a softer switching compared to the two chip solution. There are two difficulties with the RC-IGBT, namely (a) the snapback of forward I-V characteristics of the RC-IGBT and (b) the difficulty to lower the reverse recovery losses of the FWD diode E_{rec} without worsening the IGBT parameters.

   (a) To eliminate the snapback, a sophisticated integration of the n-type shorts into the p-type anode evolved into the Bi-mode insulated Gate Transistor - BiGT [19, 20]. The pilot part of the anode, which is free of the n-type shorts, turns-on like the normal IGBT without the snapback. The rest of the device, which is the RC-IGBT with combined MOS-like and IGBT-like structures, is active only after the pilot part is turned on. The RC part has therefore the n-type shorting pattern optimized for the FWD operation, IGBT turn-off and the required area ratio between the FWD and IGBT.

   (b) At the planar RC-IGBT design, the E_{rec} of the FWD can be partly minimized by a local lifetime control and partly by a special gating concept. In the trench design, the special gating is claimed to be sufficient to control the diode anode injection efficiency in order to reduce the stored charge prior to turn-off [21]. One may decide on their own, whether the better cycling capability is worth of the effort with the special gating in comparison with the easier two chip concept with less uniform temperature utilization.

(5) The short circuit withstanding capability is given by the shape of the I-V curves $I_C = f(V_{CE})$, which saturate in the saturation regime of the MOSFET. This means, that the IGBT, which inherited this feature after the MOSFET, can limit a short circuit current as long as it survives thermally. This is typically within the period of 10 µs or less during which there has to be the IGBT turned-off. The short circuit turn-off capability is a clear advantage over the thyristor based devices discussed below, which lack this feature. As they are subjected to the latch-up during turn-on and in the on-state, a protective fuses or di/dt chokes (see the choke 'L' in Fig.6a) need to be added into the application circuits, which make them more bulky and complex.
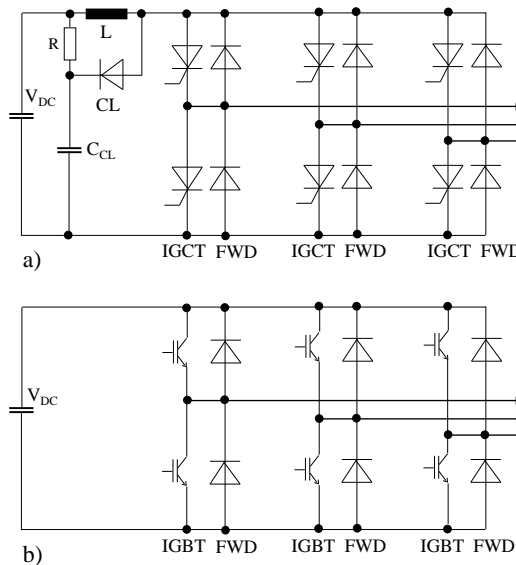

Fig. 6 Typical inverters with IGCT (a) and IGBT (b).

(6) The superior low temperature dependence of the on-state losses in the wide range of operating temperatures of the IGBT is given by the unique combination of bipolar and MOS structures. The strong degradation of the electron mobility with increasing phonon scattering (lattice temperature) $\mu_n = f(T)$ makes the silicon MOSFET the most temperature sensitive device from all relevant power devices [7]. The increase of intrinsic concentration with growing temperature $n_i = f(T)$ is responsible for the unwanted negative temperature coefficient of the on-state voltage drop in bipolar devices. In the IGBT, the strong negative temperature coefficient of μ_n is partly compensated by the positive one of the n_i. This feature is given rather by coincidence than by design.

An experimental IGBT processed at SiC substrate [6] has been demonstrated with an ambition to penetrate into the silicon domain silicon. The trick to achieve it is based on offering the IGBTs with blocking voltage well above 15 kV (demonstrated $V_{br} \approx 24$ kV), which silicon cannot achieve. In addition to other technical challenges, the low carrier lifetime in the SiC substrate had to be increased from 2 to 10 µs using 15 hours thermal oxidation at 1300 °C prior to device processing. The question is, whether the designers of the existing high voltage applications appreciate such effort. For example, the Voltage Source Converters (VSC) for very high voltage systems can use the Modular Multilevel Converter topology, where a higher number of devices is needed [22]. These devices need to be switched close to the fundamental output frequency of 50 Hz and have to be optimized for low conduction losses. The device of choice is then the silicon IGBT, with blocking voltage (typically 4.5 kV) giving an optimal trade-off between electrical losses and system cost.

4. IGCT

The exceptional feature of the Integrated Gate Commutated Thyristor is that it conducts like a thyristor (i.e. with a low V_T) and blocks both dynamically and statically like a bipolar transistor [23]. This concept has been invented in the mid 1990´s by integrating the fast (i.e. low inductance) gate unit into the structure similar to his forerunner, the Gate Turn-Off thyristor (GTO) [24]. The special gate unit provides very fast switching from the thyristor on-state regime to that of the transistor with safe turn-off, i.e. without a secondary breakdown. The snubber circuit, necessary for the safe GTO turn-off, is hereby eliminated.
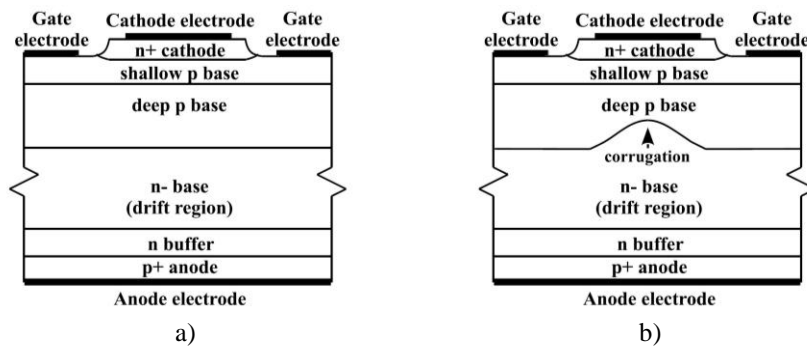

Fig. 7 Conventional (a) and corrugated p-base design of an IGCT (b).

The IGCT is nowadays the most powerful device with a turn-off capability. The reason for its lower occurrence compared to that of the IGBT is its more bulky gate unit, the lack of the short-circuit capability, and therefore the necessity of having an overvoltage clamped di/dt choke to set the switching speed. In addition, the increasing power density of IGBTs described above pushes the IGCT out from its original applications. However, the power handling capability of the IGCT is growing further. It has increased the turn-off power density to 700 W/cm^2 [25] thanks to the corrugated p-base design [26] implemented at a four inch wafer (see Fig.7). Moreover, the integration with the FWD at the 150 mm wafer moved the maximal current handling capability of the RC-IGCT towards 10 kA [27]. Having very low on-state losses, this device is particularly well suited for the Modular Multilevel Converter technology with very high rated power, which are needed for the future HVDC energy transmission and large capacity energy storage systems [28].

Recently, a new concept of the RC-IGCT has been introduced, namely the Bi-mode Gate Commutated Thyristor (BGCT) [34]. This device features an interdigitated integration of diode and GCT segments, which brings several improvements in ratings like increased power density and homogeneous thermal loading analogous to the BiGT above, lower leakage current, softer reverse recovery of the FWD, etc. [35]. We will therefore continue to see these devices in very high power applications.

5. PCT

The three-terminal p-n-p-n device was introduced in 1956 [29] to be called later the silicon controlled rectifier (SCR) and thyristor as well. To distinguish it from other existing thyristor types, we call it Phase Controlled Thyristor (PCT). As one of the first power semiconductor devices ever, the PCT played a unique role in the development of semiconductors from the very beginning, as described in the ref. [30]. Nowadays, the PCT is not anymore a hot topic of research as it was sixty years ago. However, it constantly maintains a significant market share thanks to its low processing cost, the lowest on-state losses and the simplest handling from all switches. The PCT can be found in the voltage classes ranging from few hundred volts up to 10 kV and from ten amperes up to several kA, when made from silicon. They are being used in various industrial applications, like motor control, induction heating, power quality, power supplies, etc. They play a very important role in the High-Voltage Direct Current transmission systems (HVDC). As the HVDC represents the most advancing technology based on the PCT, we discuss it briefly below.

Due to overall low system losses, large-area silicon PCTs are being used in the Line Commutated Converters (LCC) for long-distance and multi-gigawatt power transmission. As the length of these transmission lines can reach over 2,000 km, extreme demands are laid on the energy efficiency. This dictates the usage of the DC transmission line cables operating at ultra-high voltages (UHV). The most of UHVDC systems are installed and further planned in China. Following the success of UHVDC lines operating with rated DC voltage of ±800 kV and rated power up to 7 GW, China is investigating the possibility of increasing the voltage rating up to 1,100 kV for power transmission breaking the 10 GW limit [31, 32]. To satisfy the demands on the converter valve for so high power, the

current handling capability of PCTs had to be increased. For this purpose, ABB has developed the second generation of six inch PCT platform with the voltage ratings at 6.7, 7.2 and 8.5 kV [33]. Thanks to the lowered on-state voltage V_T, the maximal rating current I_{Tmax} is over 6 kA for voltage ratings of 6.7 kV and 7.2 kV PCTs, and 5 kA for 8.5 kV ones. The variety of voltage classes enables the optimization of system cost vs. energy losses trade-off.

There are also other relevant UHVDC projects, for which the PCT with $I_{Tmax} < 2.5$ kA provides a better trade-off between the system cost and energy losses. For this purpose, the PCT with even much lower V_T has been developed at four inch silicon [36]. This device has a typical on-state voltage drop $V_T = 1.55$ V at $I_T = 1.5$ kA and T = 90°C for the forward and reverse blocking capability of 8.5 kV. There is no other device with such low on-state losses for the 8.5 kV blocking. This implies further loss reduction of the converter valve by more than 5%, hereby moving the CSC concept to ever higher transmission efficiencies. This is important for the future of the UHVDC transmission systems based on the LCC with PCTs (so-called HVDC Classic). This is because they are being replaced by that of the self-commutated VSC with IGBTs (HVDC Light), which have a lower efficiency and can transmit lower power, but they offer other beneficial features like smaller footprint, reactive power control, cold start, no need for a solid AC network at both sides of the transmission line, etc.
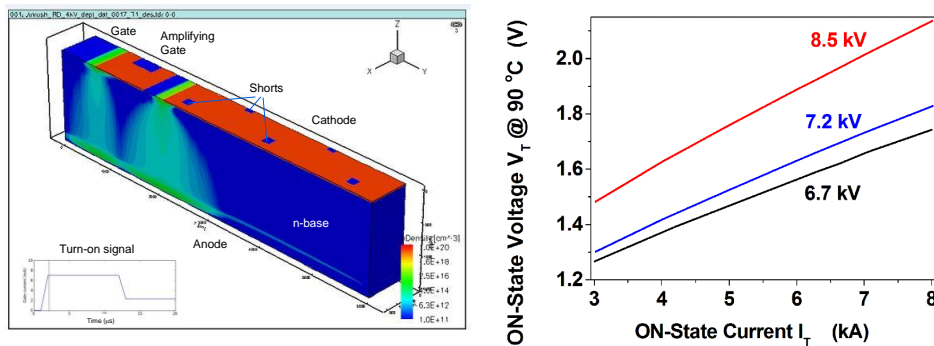

Fig. 8 Electron concentration in the PCT at turn-on phase (a). Measured V_T vs. I_T for the new 6" PCT platform (b).

6. CONCLUSIONS

Current trends in the design and technology of power semiconductor devices were discussed on the threshold of the year 2015. It has been stated that power electronics continues to utilize above all the silicon based devices, but the wide bandgap devices based on the GaN and especially on the SiC have assumed the importance as never before.

The silicon MOSFET dominates the low voltage sector, but in the future, the SiC MOSFET is expected to surpass above 650 V up to about 1200 V. The silicon IGBT is

available from 650 V to 6.5 kV. It dominates between 900 and 1700 V. It is also important for higher voltage classes due to the industrial drives, traction (1.7 - 6.5 kV) and energy transmission and distribution (4.5 kV). The Modular Multilevel Converters with IGBTs are hindering the penetration of the SiC solutions into the low loss applications. The area of very high power is occupied by the IGCT and PCT. The main drivers are the energy savings and the world's hunger for electricity. The PCT occupies also the lower power areas, where a low cost and simplicity of handling is required. The wide bandgap devices can be found in the applications with a lower power, where their very high conversion efficiency, very high operational frequency and high power density can compensate for their much higher price.

The development trends of high-power technologies will continue to secure the high power systems with exceptional performance, comfort, energy savings and the required environmental sustainability.

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