Ultra High Voltage Semiconductor Power Devices for Grid Applications

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Abstract

Silicon based high voltage semiconductor devices continue to play a major role in megawatt power electronics conversion especially in the fields of traction drives, industrial applications and grid systems. The main development trend of power devices has always been focused on increasing the power ratings while improving the over all device performance in terms of reduced losses, increased robustness, better controllability and reliable behavior under normal and fault conditions. This paper will focus on ultra high voltage devices for grid applications while providing an overview of the recent advancements from the device design and performance viewpoint for enabling the next generation of grid systems.

Introduction

The power electronics revolution, which has over the past few decades swept across the power delivery and automation sectors, has opened up a wide range of possibilities in terms of controlling the way electrical energy is transported and used. At the heart of this revolution lies the power semiconductor device which has the main task of modulating the energy flow to suit the demands of the application. Power semiconductors in general terms cover an ever increasing number of applications which has in turn enabled the continuous improvement in device performance. The very high power end applications in the megawatt range, represents a small but important market sector for semiconductor components. Therefore, their progress is largely dependent on technologies developed initially for lower power applications and then scaled and optimized to enable the components to withstand higher voltages and currents to meet the requirements of higher power ratings.

In relation to the topic of this article, advances in ultra high voltage semiconductors have led specifically over the past few decades to tremendous improvements in grid system applications in terms of power handling capability and control [1]. With the recent energy related social, economic and environmental concerns coupled with the continuous progress in electrical power generation and control, the device development trends are set to continue as a major enabler for matching the performance expectations of future grid systems. In the following sections, we will provide a basic overview of grid applications and the current power semiconductor technologies employed in such systems. In addition, future power device concepts are presented including an overview of the design and process requirements plus the recent experimental data obtained from tests carried out on prototype samples. The potential impact such components will have on the system level performance are also discussed.

Grid Systems and Applications

The current grid system requirements are mainly influenced by the largely increased energy demands especially in heavily populated and industrialised urban areas plus the challenge to deliver power from remote energy generation locations which include alternative energy sources such as wind turbines, solar cells and hydro plants. Furthermore, renewable energy supply is intermittent and unpredictable; hence the requirements on them for network integration/compatibility and energy storage have also increased since their impact on the grid is of major importance. “Smart Grids” is often the terminology used for this evolutionary step for modernizing the entire Transmission and Distribution (T&D) network. High Voltage Direct Current (HVDC) transmission and Flexible AC Transmission Systems (FACTS) represent the two main system level enablers for achieving the goals outlined above [1,2]. Both applications lie at the very high power range as indicated on the left in figure (1) when compared to a number of lower power applications.

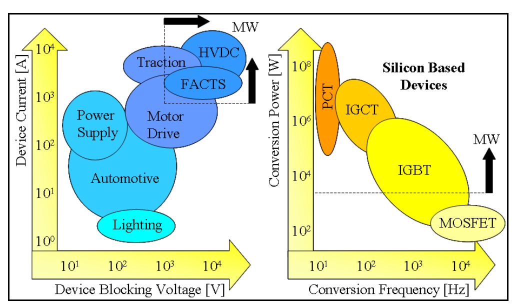

Fig. 1: Power Semiconductor devices and applications.

The different silicon based power device concepts and their typical ratings are also shown on the right in Fig. 1. In the megawatt range, three types of switching devices are dominant; the Phase Controlled Thyrsitor (PCT), the

Integrated Gate Commutated Thyristor (IGCT) and the Insulated Gate Bipolar Transistor (IGBT) [1]. One must also not forget the power diode covering the whole power range for rectification, snubber or freewheeling purposes.

HVDC transmission systems are employed when it is more economical to transmit electrical energy over large distances in DC rather than AC despite the fact that AC is the form in which electricity is mainly generated and consumed. Different power semiconductor based circuit topologies such as Current Source Converters (CSC) and Voltage Source Converters (VSC) are employed for the AC/DC conversion process depending largely on the transmission distance and power levels involved [1]. For long distances and multi-Gigawatt power transmission, classical PCT based CSC topologies are widely applied due to their overall low system losses. For relatively shorter distances and sub-Gigawatt power levels, IGBT based VSC conversion is becoming the system of choice due to a number of integration and control features especially when taking into account the introduction of renewable energy into the grid. In addition to HVDC, a number of grid power electronics applications exist predominantly on the AC side which are generally grouped under the heading FACTS. These include Static Compensators (STATCOM) for voltage stabilization and load balancing, grid interties, energy storage, and active filters to name a few. Many of these systems, because they are fundamentally AC, operate at medium voltage and connect to the high voltage grid via transformers. They are all based on VSC topologies utilizing both IGBTs and IGCTs. As for most power electronics circuits, the power semiconductor has a huge impact on the levels of performance achieved in the above mentioned systems. Despite the fact that a wide range of high voltage device with attractive electrical characteristics exist, higher power and superior overall performance remain as the main development trend for satisfying the demands of next generation grid system designs.

Power Semiconductor Devices for Grid Applications

High voltage power semiconductors differ from their low voltage counterpart in a number of structural aspects [3]. First they include a wide and low n-doped base region at the pn-junction to support the high electric fields required for the high voltage ratings. For current carrying capability with low losses, they require large active areas and highly doped contact regions to provide (a) high minority carrier (holes) injection levels for modulating the low doped n-base and (b) good ohmic contacts to the outside world. The current is normally flowing in the vertical direction in the voltage range exceeding 1kV. Today, silicon based devices can be designed with good overall performance parameters up to 10kV for a single component. It is important to note here that power semiconductors employed in gird systems do not differ from those employed in other power electronics applications such as traction and industrial drives. Nevertheless, for grid applications operating typically at very high voltages in the hundreds of kilovolts range, devices are normally connected in series to support the total dc-line voltage [4]. The choice of the single device voltage rating employed in these systems depends largely on the performance/cost calculation for a given topology and operational parameters. Lower voltage rated devices have normally a favourably lower overall loss figures but require larger number of components and accessories to reach the desired voltage levels when compared to higher voltage devices.

Fig. 2 shows the PCT, IGCT and IGBT basic structure and evolution over the years in their respective packages. The main three high voltage components employed in grid systems have undergone major developments in the past two decades. The PCT and IGCT are bipolar devices operating in thyristor mode which is mainly characterized by its favourable excess carrier distribution for low on-state losses in conduction mode. While, the IGBT is a MOS controlled device with a bipolar effect for achieving low on-state losses.

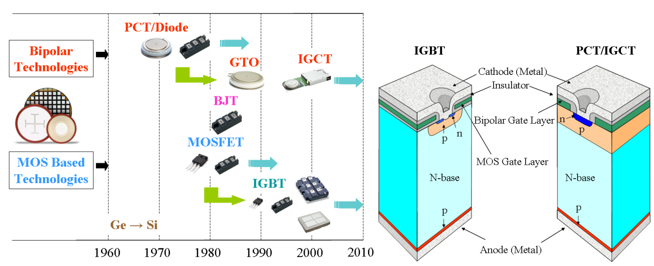

Fig. 2: Power device evolution and basic structures.

A. The PCT/IGCT; The PCT is not a turn-off device compared to both the IGCT and IGBT, but is the device of choice for line commutated CSC HVDC systems due to its exceptionally low on-state losses and very high power handling capability. Up to very recently, the state of the art single devices where rated at 8.5kV with a total diameter of 125mm. With the increase in demand for even higher power HVDC system ratings, larger area 150mm 8.5kV PCTs with current rating up to 4000A were developed for employment in the latest Ultra HVDC systems operating at 800kV with the total transmission power exceeding 7GW. Fig. 3 shows the new PCT and the UHVDC system valves consisting of series connected PCTs.

Fig. 3: 150mm PCT rated at 8.5kV/4000A for UHVDC.

The other thyristor based structure is the IGCT which has since its evolution from the Gate turn-off Thyristor (GTO) in the mid 1990`s established itself as the device of choice for industrial Medium Voltage Drives (MVD) and wind-power conversion. Due to its limited application in medium voltage FACTS systems, we will only briefly cover it in this article. Due to the integration with a low inductive gate unit, this device conducts like a thyristor (i.e. low on-state losses) and turns off like a transistor (i.e. hard switching). The recently introduced High Power Technology (HPT-IGCT) gives an increase in the IGCT-SOA (Safe Operating Area) of up to 50 %, thus providing new perspectives for control and fault handling compared to the standard devices. The HPT has been proven for IGCTs with voltage ratings up to 10kV [5].

B. The IGBT; IGBTs are destined to play an even stronger role in future VSC based HVDC and FACTS applications. Today, a wide range of IGBT products continue to provide megawatt applications with optimum components which have enabled with each improved generation a clear leap in power levels. The IGBT with its inherent advantages including a controlled low power driving requirement and short circuit self limiting capability has experienced in the past two decades many performance breakthroughs as illustrated in Fig. 4 [6].

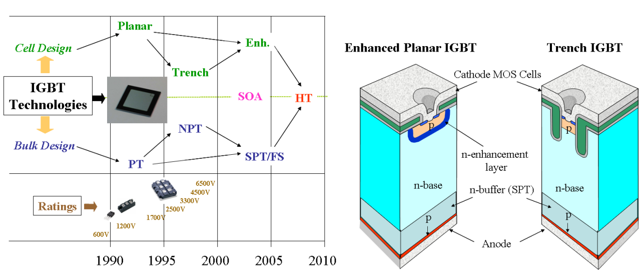

Fig. 4: Evolution of IGBT technology and modern structures.

The fast progress in IGBT cell designs (planar, trench, enhancement layers) and bulk technologies such as Punch-Through (PT), Non-Punch-Through (NPT) and Soft-Punch-Through (SPT) or Field Stop (FS) which started from a low current and low voltage origin has resulted in the device wide employment in many high voltage applications. Today, high power IGBT press-pack and insulated modules have ratings ranging from 1700V/3600A to 6500V/750A. The most recent trends targeted lower losses due to thinner n-base regions (SPT/FS) and plasma enhancement layers and/or trench cell designs as shown in Fig. 4 accompanied with higher SOA and higher operating temperature (HT) levels. Similar development efforts targeted an improved diode design to match the latest IGBT performance. The freewheeling diodes play a very important role in the application during normal switching and under surge current conditions. The current IGBT platform employed in grid applications is based on an Enhanced-Planar cell design (EP-IGBT) which has enabled the establishment of a new technology curve benchmark over the whole IGBT voltage range from 1200V up to 6500V as shown in Fig. 5. Further loss reductions are predicted from simulation results by optimization of an enhancement trench structure [7].

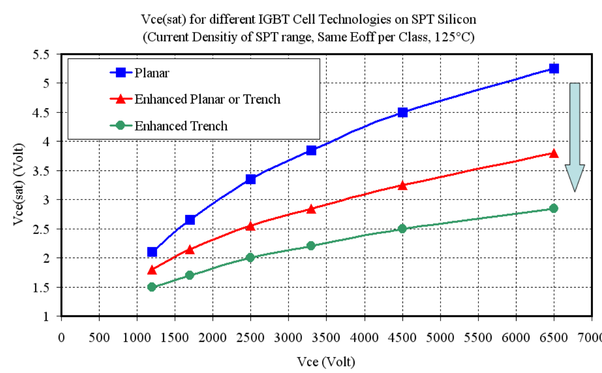

Fig. 5: High voltage IGBT technologies on-state losses $V_{ce(sat)}$.

Another important component aspect is the semiconductor encapsulation technology since developing a package for series connection of IGBT and diode chips is a challenge. A highly customized press-pack module was developed specifically for grid applications [4]. The mechanical design is optimized in order to facilitate the clamping of the press packs in long stacks. Even if the clamping in the stack has severe pressure non-uniformities, the module remains fully functional due to its unique design with individual press-pins for each chip as shown in Fig. 6. Furthermore, the choice of materials is optimized to achieve high reliability in the field. The trade-off between power-cycling capability and operation under shorted fault conditions is a major development thrust.

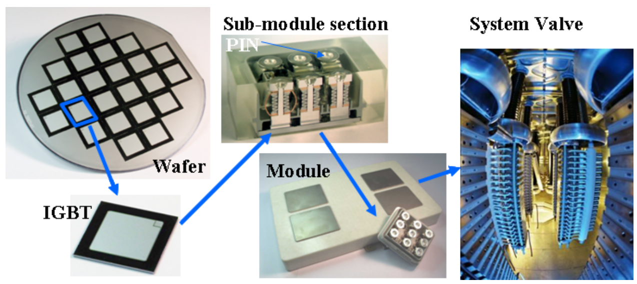

Fig. 6: IGBT application from single chip to system valve.

Future IGBT Technologies for Higher Power

The latest VSC based HVDC systems can enable power transmission levels with a maximum possible capability close to 1GW. Nevertheless, such systems are envisioned to be able to reach higher power levels with the continuous development of device and system technologies. The clear demand in increased power densities of IGBT and diode components has led to the focus on an IGBT and diode integration solution, or what has been normally referred to as a Reverse Conducting RC-IGBT. The practical realization of a single-chip technology will provide an ideal solution for compact systems with higher power levels, which is proving to be beyond the capability of the standard two-chip approach. Nevertheless, the realization of such a concept has always been hindered by design and process issues resulting in a number of performance drawbacks such as on-state snap-back, IGBT vs. diode losses trade-off, turn-off softness, and SOA. Development efforts in the direction of solving the above aspects have resulted in an advanced RC-IGBT concept referred to as the Bi-mode Insulated Gate Transistor (BIGT) [8] which is a hybrid device integrating an RC-IGBT and an IGBT in a single chip as shown in Fig. 7.

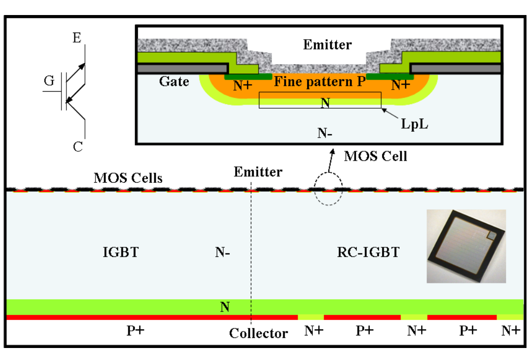

Fig. 7: Cross section of the BIGT.

The SPT buffer design and enhanced planar technology discussed previously have been the main enablers to bring forth the possibility of this integration step. A number of innovative technologies were introduced into the BIGT in order to realize the integration of the previously two chip functionalities such as the Local P-well Lifetime (LPL) step to reduce the diode recovery losses and the specialized backside layout design and process. The results obtained show that the BIGT exhibits low losses in both modes of operation with no typical snap-back behavior in the transistor on-state mode when compared to a standard RC-IGBT, while also maintaining high levels of SOA performance. The BIGT offers in addition a number of device performance advantages such a soft switching behavior under extreme conditions and better diode surge current capability. The initial BIGT press-pack module demonstrators containing 10 BIGT chips were rated at 3300V and 600A and tested under conditions similar to those applied to state-of-the-art IGBTs. The switching characteristics of the BIGT modules under extreme SOA conditions (1200A and 2400V) in both IGBT and diode modes are shown in Fig. 8 at 125°C. The diode reverse recovery current is mirrored in the turn-on waveform.

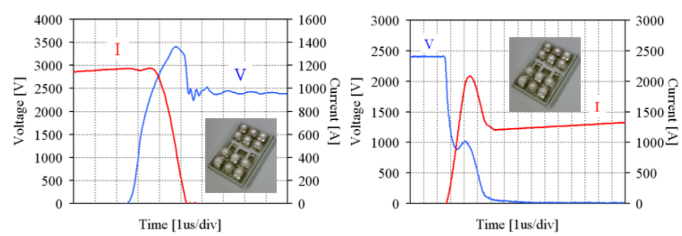

Fig. 8: 3.3kV/600A BIGT sub-module turn-off (left) and turn-on (right) under extreme SOA conditions.

Conclusions

The paper presented a review of the recent advancements achieved in the field of high voltage power semiconductor devices targeting megawatt grid applications. The power device is considered as a main enabler for the growing demands of modern grid systems in terms of increased power levels, improved efficiency, greater control and integration of renewable energy sources. New system and component developments will have a major impact on the way we plan to produce, distribute and utilize energy in the future.

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