Overview of Recent Progress in High Voltage Insulated Gate Bipolar Transistors(IGBTs) and Its Industrial Impacts

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I.Introduction

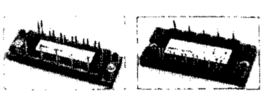
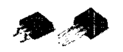
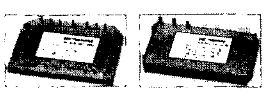
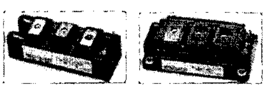
Today's progress in power electronics has been possible primarily due to advances in power semiconductor devices. In response to continuous demand for efficient control of power conversion and motion control systems, there has been a rapid evolution in power semiconductor devices. Accordingly, wide spectrums of power devices are available in the market, which are intended for the different applications.

With the help of the significant progress in design and process technologies, the power handling capability and device performance of power semiconductor devices have been dramatically improved. The performance of the power electronic systems closely relies on the residing power semiconductor components, which determine the efficiency, size, and cost of the systems. Therefore, research activities to develop the perfect power semiconductor switch have been insistently conducted. The ideal power semiconductor device should have the following attributes.

1. Minimal power loss in the on state as well as during the switching
2. Minimal power loss in the off state
3. Minimal power required for controlling operation
4. Easy to use and reliable
5. Inexpensive

The modern power semiconductor devices are available in various forms such as discrete packages, modules, and IPMs(intelligent power modules) with the ratings of a few tens volts (amps) to a few kilo volts(amps). Dealing with the huge demand for high performance, low cost, wide functionality and energy savings in power electronic applications, research and development efforts for new power device technology have been mainly concentrated on MOS gated devices.

Among those MOS gated power devices, the

Package type	Discrete	Package type	Module
D-PAK I-PAK		6-PAK (Compact Type)	
D^2-PAK I^2-PAK			
TO-220 TO-220F		7-PAK (Complex Type)	
TO-3P			
TO-3F		2-PAK (Molding Type)	
TO-264			

⟨Figure 1⟩ Various IGBT products available in the market in a different package form

IGBT(insulated gate bipolar transistor) has been increasingly used and broadened its range of applications. Since the IGBT is the MOS-bipolar hybrid device, it offers high input impedance of MOS gate, together with high bipolar current handling capability. Its switching frequency is much higher than that of BJT, and square SOA(safe operating area) permits easy snubberless operation.

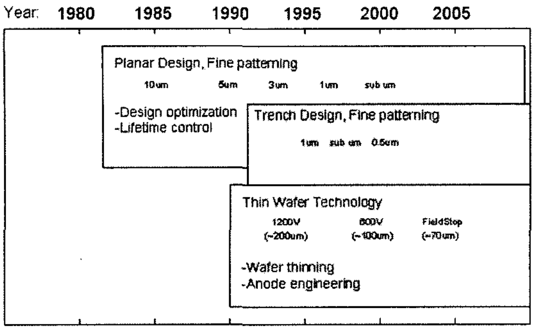
After the advent of commercial IGBT products in the marketplace in 1983, there have been significant improvements in the device ratings and electrical characteristics of IGBTs. Today, 600-V, 1200-V, 2500-V and 3300-V discrete IGBTs and IGBT modules are commercially available and a variety of IGBT products have been being released. Moreover, IGBT intelligent power modules(IPM) have also been available with built in gate driver, control and protection for up to several hundred kW power rating. The present IGBTs using trench gate structure and thin wafer technology have conduction drop which is slightly higher than a diode, and much higher switching speed.

In the medium power and medium frequency range, the IGBT is the most widely used power semiconductor device, finding widespread applications in AC motor drives, traction control, induction heating systems, uninterruptible power supplies(UPS), and switch mode power supplies (SMPS), and so on. Currently, several large semiconductor companies are manufacturing a variety of IGBT products in a different package(as shown in Fig.1).

II. Technology Trends in Insulated Gate Bipolar Transistor

1. History of IGBT

The modern era of solid state power electronics started with the invention of thyristor(or silicon-controlled rectifier) in the late 1950s. Gradually,



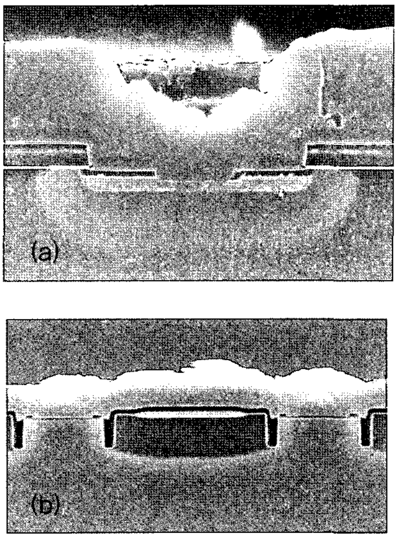
〈Figure 2〉 Developments in Key IGBT Technologies

other devices, such as triac, gate turn-off thyristor(GTO), bipolar power transistor(BPT or BJT), power MOSFET, insulated gate bipolar transistor(IGBT), static induction transistor (SIT), static induction thyristor(SITH), MOS-controlled thyristor(MCT), and integrated gate commutated thyristor (IGCT) were introduced.

As the evolution of new and advanced devices continued, the voltage and current ratings and electrical characteristics of the existing devices began improving dramatically. In this sense, the power electronics evolution generally followed the device evolution.

The introduction of IGBT was an important milestone in the history of power semiconductor devices. The first idea of the IGBT was demonstrated by Baliga in 1979[1] and then in 1980 by Plummer and Scharf[2]. Then, more research work was extensively carried out for comprehension of the new MOS-bipolar hybrid device in the early 1980's[3-6].

After the first commercial IGBT products were released, the main technology for IGBTs has been gradually changed while offering significantly improved device performance. Major developments in IGBT key technologies are shown in Fig. 2.



〈Figure 3〉 (a)Planar IGBT and (b)Trench IGBT

Before the thin wafer process was available in the early 1990s, the IGBT was based on the punch through(PT) structure, which type of IGBT technology needs additional lifetime control process to improve the switching performance, while the discussion on the non punch through(NPT) IGBT was limited. Concurrently, fine patterning was one of key design factors to advance the devices, which has been possible as micro fabrication process technology is progressed. From the mid 1990s, unlike the planar gate design, trench gate technology also appeared in IGBTs and which are now familiar active structures for the recent high voltage IGBTs under 1200-V ratings. The exemplar structures of the planar and trench

IGBTs are demonstrated in Fig. 3.

In the mid 1990s, using the new fabrication process concept for the vertical power semiconductor devices, the 1200-V NPT IGBT was mainly introduced in production[7]. Which is the thin wafer process based IGBT, proposing to exploit the drift layer of the wafer while eliminating the redundant wafer part from the device performance point of view. Owing to the introduction of innovative thin wafer process, the IGBTs have been able to broaden its power ratings and a range of its applications. Combining the benefit of thin wafer processing and punch through concept, the field-stop IGBT appeared in 2000[8] and the similar concepts like the lightly punch through(LPT) or low injection punch through(LiPT) have also been successively introduced[9, 10].

2. Major IGBT structures

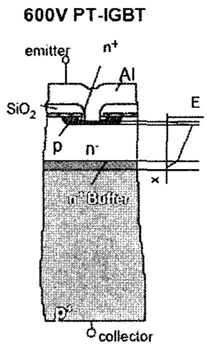
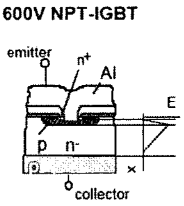
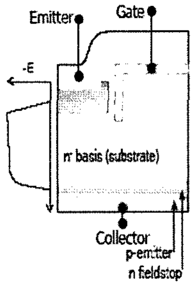
Commercial IGBT devices are broadly classified into the two types, the PT IGBT and NPT IGBT. These IGBTs significantly differ with respect to their fabrication technology, structural details, carrier profiles during operation, carrier lifetimes, transport mechanism and accordingly, device performance. The typical structure of the PT and NPT IGBTs are shown in table.1 where the different IGBT concepts are compared.

The PT IGBT is fabricated in an N+/N- double layered epi wafer, which is more expensive than the substrate wafer used in the NPT IGBT. The N+ buffer in the double epi layers is used to avoid thick N- layer while obtaining the desired blocking capability as well as controlling injection efficiency of P+ collector region. In addition, to achieve superior device performance by improving switching characteristics, lifetime control process is inevitably needed for the PT IGBT. For this purpose, the uniform control of electron beam irradiation or localized control with proton and helium is widely used. In general, the trade-off performance between conduction and dynamic losses of the PT IGBT is superior to that of the NPT IGBT. However, its performance is more temperature sensitive and thermal stability as well as short circuit and avalanche ruggedness is not as good as the NPT IGBT.

On the other hand, the NPT IGBT is manufactured based on the thin wafer process technology. The recent IGBT products using thin wafer process technology require the wafer thickness down to 70um. Such wafer is even thinner than the thickness of human hair. As a result, thin wafer processing cannot be simply carried using the process equipments for the typical power semiconductor devices. In terms of mass production, wafer thinning process and the relevant unit process steps are main challenges for further advancement of thin wafer processing based IGBT devices. In general, the 600-V NPT IGBT needs 90~110um wafers and 1200-V IGBT employs 160um~200um wafers.

In Fig. 4, a 6 inch/ 100um IGBT wafer is shown. As can be seen, the thin wafer is very

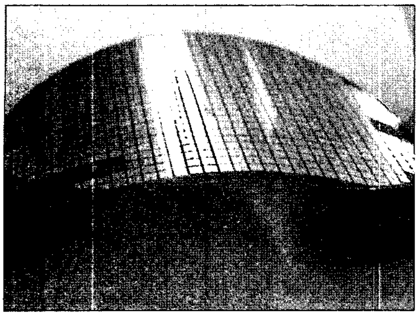
〈Table 1〉 Comparison of different IGBT concepts

	PT-IGBT	NPT-IGBT	Field-Stop IGBT
Structure			
P-emitter	Very high efficient	Low efficient	Low efficient
n-drift layer	thin	medium	thin
Additional N-layer	Buffer layer:highly doped -to reduce the very high emitter efficiency -to stop the electric field	no	Field stop layer:weakly doped-to stop only the electric field
Carrier lifetime	Low (lifetime controlled)	High	High

flexible and thus, the wafer warpage and bow become severer as the wafer is getting thinner. Mass production with such uneven wafers is very complex since the successive fabrication process steps cannot smoothly preceed and high risk of wafer breakage is latent.

Since the NPT IGBT employs no lifetime control process, high carrier lifetime yields a low voltage drop during conduction. Also, optimizing the injection efficiency of the anode, fast switching capability can be achieved. Furthermore, owning to its thin nature, thermal stability as well as ruggedness is far better than the PT IGBT. In this regard, now, the NPT structure becomes majority for the high voltage IGBTs. However, it should be noted that any single IGBT structure is universally optimal. Thus, the IGBT for a given application should be chosen according to the specific needs.

In the meantime, in order to take full advantage of the thin wafer technology as well as the principle of punch-through structure the field stop(FS) concept has also been applied to the NPT IGBT structures, which realizes the same blocking capability with reduced wafer thickness by virtue of the trapezoidal electric field distribution during the off state as illustrated in table.1[8]. The IGBTs with the FS



〈Figure 4〉 6 inch-100um 600-V NPT IGBT wafer

layer(FSL) show better trade-off performance against the typical NPT or PT IGBTs and thus the FS IGBT structure is considered as one of the most advanced IGBT designs and numerous extended FS concepts have been investigated[9-11].

Currently, only a few IGBT manufacturers provide the IGBT products using the field stop or similar concepts.

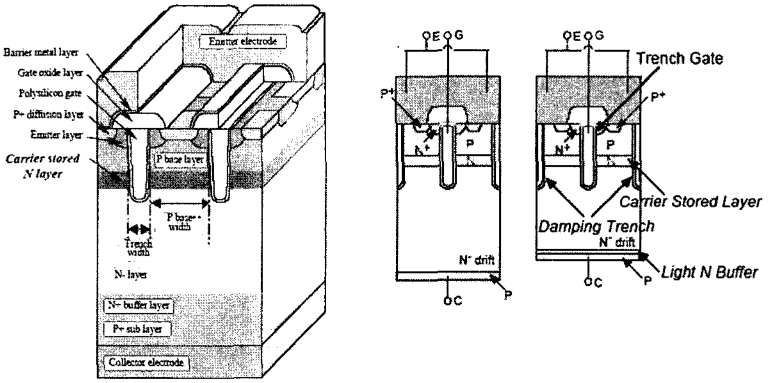
III. Advanced Concepts in IGBTs

While the field stop IGBT concept has been commercially successful in the market, several advanced IGBT concepts have been reported[12-18]. Those state of the art IGBT concepts have been being commercialized limitedly where high ruggedness is not required, but are very instructive for improvement of the existing IGBT design and technology and furthermore for realizing advanced IGBT devices.

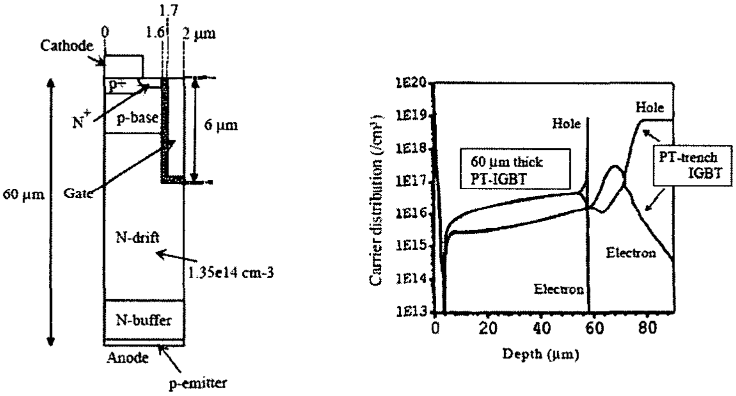
1. State of the Art in IGBTs

The state of the art IGBT concepts mainly deal with optimizing carrier profiles in a thin wafer based structure. Also, some brilliant ideas have been suggested to create better anode structures[12, 13]. To improve the on-state voltage drop, the carrier stored trench gate bipolar transistor(CSTBT) was proposed[14] and its basic structure is shown in Fig. 5. Placing the carrier stored N layer under the P-base, the CSTBT can hold more hole carriers during the conduction state since the minority hole carriers injected from P+ collector are intensified by the carrier stored layer like in the diode. More improved idea from the CSTBT was reported, which is to add the lightly doped N-buffer to obtain the similar effect as in the field stop IGBT[15]. It is also demonstrated that the CSTBT can show enough shot circuit capability by increasing the trench cell pitch[9].

Another concept like the field stop or lightly punchthrough(LPT) is the thin punchthrough (Thin-PT) IGBT[16]. Basically, it is the same as the field stop IGBT as shown in Fig. 6. In case of the field stop IGBT, it is very difficult to form the field stop layer after thinning the IGBT chips. Therefore, instead of creating the field stop layer on the backside of the thin wafer, the thin-PT IGBT can be realized by thinning the PT IGBT. However, unlike the conventional PT IGBTs, the thin PT IGBT does not need lifetime control process since N-buffer and P-emitter(anode) concentrations are optimized. As a result of high carrier lifetime, the carrier density is much higher than that of the typical PT IGBT(as shown in Fig. 6), which



〈Figure 5〉 Three dimensional view of CSTBT and cross section of CSTBT with LPT design[9, 14]

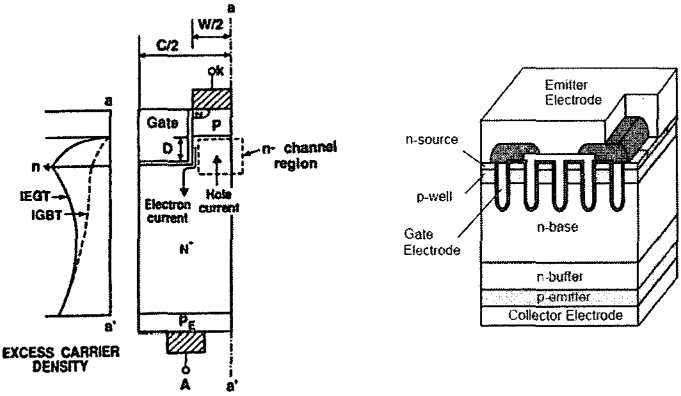


〈Figure 6〉 Cross sectional view of 600-V trench thin PT IGBT and the corresponding carrier distribution in the conduction state[16]

leads to low on state voltage drop. The thin PT concept based commercial IGBT products are also available for the 900-V IGBTs.

In addition, the more improved anode concept for better switching performance was recently demonstrated by inserting P-buffer between the N-buffer and anode, which can effectively minimize the tail current component at switching off transition[12].

The injection enhanced gate transistor(IEGT) or high conductivity gate transistor(HiGT) is based on the similar physical principle, which is also intended for hole carrier storage effect as the CSTBT[17, 18]. Optimizing the trench cell pitch and P-base/ trench depth, hole carrier density can increase, leading to high conductivity, which results in lower on state voltage drop. Together with the IEGT or HiGT concept, the precise control of anode condition or the new anode concept offers improvement in switching off characteristics[10].



〈Figure 7〉 Basic concept for IEGT device structure and schematic excess carrier density[17]

2. Novel Super Junction Field Stop IGBT

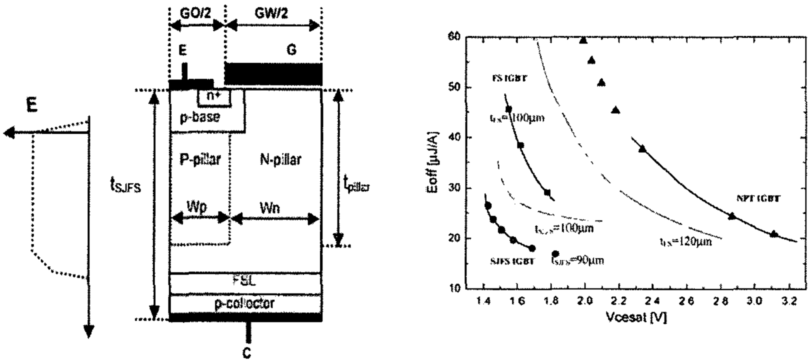
In conjunction with the advanced IGBT concepts, the ultimate design for the IGBT seems to be based on the principle of charge balance[19]. Using the concept of the charge balance, which is generally called the super junction, it is shown that the concentration of the drift layer can be increased while preserving the same blocking voltage. As a result, the super junction MOSFET devices show dramatically reduced on-resistance compared to the conventional MOSFET devices. This innovative concept was already practical for 600V power MOSFETs such as SuperFET^{TM} from Fairchild Semiconductor in the market.

Since the principle of the charge balance offered a new paradigm for the power semiconductor devices, pervasive investigations into majority carrier super junction devices have been performed[20-22]. Along with the super junction MOSFET, recently, it is explored the super junction IGBT devices and furthermore showed its feasibility[23]. Fig. 8 shows the schematic structure of super junction field stop IGBT and the simulated device performance in comparison with the typical NPT and field stop IGBTs. As is shown, the benefit of the super junction field stop(SJFS) IGBT is huge and thus further study is being motivated in this area.

The optimization based on super junction IGBT with relevant design considerations and issue for its implementation will be main research activities in the development of IGBT in sooner future.

Ⅳ. Technology Trends in Power IGBT Modules

The typical mold type power modules (in Fig. 9, (a)) were started in 1980's using power bipolar transistors. In comparison with the traditional disk type modules, the mold type modules were



〈Figure 8〉 Schematic structure of super junction field stop IGBT and simulated trade-off performance for the SJFS IGBT, FS IGBT, and NPT IGBT with different drift layer[23]

more appropriate for mass production and as a result, gradually become key components for the industrial power conversion systems afterwards.

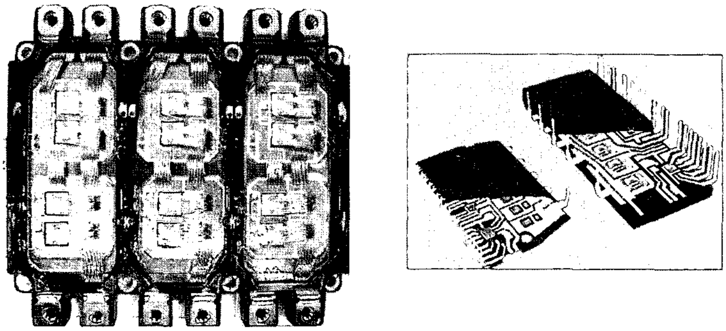
In high power applications, large area IGBT chips are required. However, the manufacturing of large area IGBT chips are suffering from low processing yield, principally due to gate oxide defects. Therefore, the IGBT chip size is generally limited to 2~3 cm^2 and the power density of IGBT is also restricted by this physical reason. Hence, the concept of power IGBT modules originated from paralleling several IGBT chips together, to create a single packaged high power device. While the main objective of a power module is to increase the current capacity, it also offers increased functionality by including diodes, gate driving circuit and protection circuits for over current, short circuit, over temperature and over voltage.

The power IGBT module technology was revolutionized by the advent of IPM where highly functional parts are integrated with power semiconductor components. Thereafter, the DIP-IPM, which is based on the lead frame and transfer mold type(in Fig. 9, (b)), was introduced and widely used for the variable speed drive in home electronic goods.

The core technology for realizing the IPM and DIP-IPM is the integration of the driving part, which is possible owning to the significant progress of HVICs, and today, up to 50A-rating chips can be driven in this way. In addition, advancement of the substrate materials like the DBC(direct-bonded copper) or IMS(insulated metal substrate) also contributed to improvement of power module technology, which shows better heat dissipation capability.

Modern power module technology advances in three different ways.

Firstly, the standard power module has been siginificantly improved through miniaturization by enhancement of heat dissipation capability and adoption of the contact less gate terminal,



〈Figure 9〉 (a)Plastic package module, and (b)Transfer mold module

which is also beneficial for parallel operation in high power applications.

Secondly, the DIP-IPM mainly intended for the applications in home appliances and using 1200-V HVICs, the miniaturization, the integration and increase in current ratings up to 100A are aggressively in progress.

Lastly, the IPM is largely used for the applications where high reliability is required. Recently, the IPM rapidly improves as it is increasingly applied for the hybrid electric vehicle(HEV) applications. The power modules for HEV applications require extremely high ruggedness as well as high density of integration for long-term operations since their working environment is extremely harsh. In this sense, the IPM for HEV applications is designed with the built-in drive circuit and protection circuits with the current and temperature sensors.

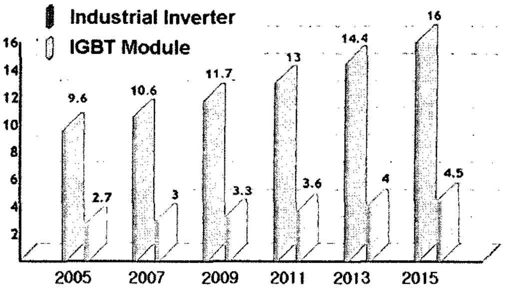
The development trend of power module is to improve long-term reliability for safe operation through the integration of functionality and in this regard, as a value added product, IPM development is rapidly accelerated. In order to increase power density of the power module, pursuing low cost as well as high reliability at the same time, the standardization of the driving and protection circuitry and alteration of many isolated blocks into integrable blocks in a power system should be followed. Conclusively, the most critical point in competence of power module is the system integration through reconstruction of non-standardized parts and the adoption of new approaches.

V. Status of IGBT industry in Korea

It is known that it is possible to save 20~40% energy of the electricity consumed by motor if all the motors are converted to inverter. Since the energy consumption by motors occupies over 60% out of total electricity, conversion to the inverterized motor system is inevitable.

In spite of short history of power semiconductor business in Korea, the IGBT and related power module technology, which are key components in the inverter systems, have been rapidly developed. Since the first IGBT development project by Fairchild Korea(former Power Device Division of Samsung Electronics) and Seoul National University, Fairchild has launched the IGBT business from 1995 and released the first commercial IGBT module product in 1997.

There are two major challenges-technical and industrial environments, regarding development of IGBT in Korea. In the view point of technology, Korea had very short experience on the power semiconductor since the end of 1990s when Samsung Electronics started their IGBT development while the advanced countries started IGBT development and business just after the invention of IGBT in the mid of 1980s based on their matured power electronics technologies as well as other power semiconductor technologies on MOSFET, BJT and Thyristor. In the view point of the industrial environments, in addition to the relatively small business volume regarding the industrial power semiconductor, there is no link or close partnership between semiconductor suppliers and the customers. Because of the absence of such a link, there could not be adequate requirements and feedbacks to the semiconductor suppliers from the customers. Even in the case there is a little communication on those, in-time development and supplies were impossible due to the limitation on the volume and module line up in addition to the relatively low technology level of Korean products.

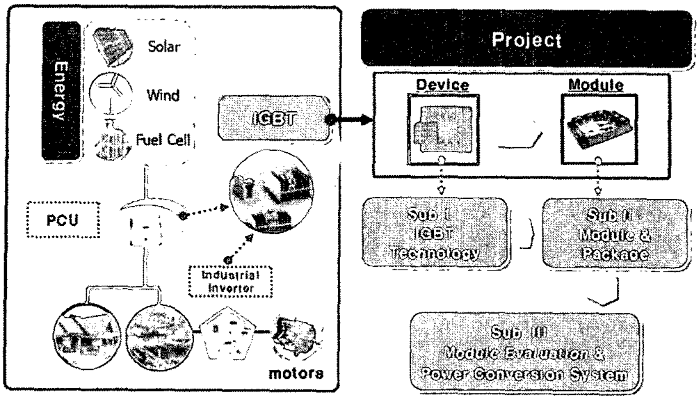


⟨Figure 10⟩ Worldwide market and expectation of the industrial inverters and IGBT modules

Total industrial inverter and related IGBT module markets are estimated as 9.6 billion and 2.7 billion dollars, respectively, in the year of 2005 as shown in the Fig. 10. CAGRs(compound annual growth rates) of both industrial inverter and IGBT module market are around 10% over next 10 years and the IGBT module market is expected to reach 4.5 billion dollars in the year of 2015. In Korea, the industrial inverter market and IGBT module market are estimated as 1.1 billion dollars and around 30 million dollars, respectively in the year of 2005. The IGBT module markets are expected to be around 56 million dollars in the year of 2015.

To cope with such a future trend, Ministry of Commerce, Industry & Energy and KEPCO are sponsoring a project so called "IGBT project" for 5 years. The project consists of three sub projects; Sub 1-IGBT device development, Sub 2-IGBT module development, Sub 3-IGBT module system and evaluation. The whole project is organized as shown in the Fig. 11.

In performing the IGBT project, Fairchild



〈Figure 11〉 Organization of the "IGBT Project"

Semiconductor and KEC will develop 1200V and 600V IGBTs, respectively and LS System Industry Co. will develop the IGBT module and intelligent power module as well as the evaluation system based on the outcomes from the semiconductor companies. This project is not only to develop such technologies but also to build the business of the semiconductors and related modules in addition to securing the know-how and related technologies in the viewpoints of supplier and customer.

Fairchild and KEC will develop NPT IGBT that is suitable for industrial applications and will expand to trench gate IGBT and Field Stop IGBT based on the input from the sub 2 project teams. Along with the development of the silicon based IGBT technology, compound power semiconductor technologies such as GaN and SiC will be developed for future technologies beyond silicon technologies. For the success of the module related technology and business, a consortium was organized with LS System Industry Co. and Fine Electronics and the university R&D centers to maximize each capability such as investment capability, know-how and fundamental power electronics knowledge. In the technology viewpoints, the project is aiming at the design of drive power IC and circuit, analysis of parasitic components, package design and its thermal analysis and securing the module mass production processes.

Ⅵ. Conclusions

Power semiconductor devices and related power semiconductor modules reflect the core competency of the power industry, as a measure of the technology level of power electronics of the nation. Among the power semiconductor devices, IGBT will be a key semiconductor component for power industry since it has a huge potential to cover large areas of power electronics from small home appliances to heavy industries. Currently, most of the industrial consumptions of power IGBT modules are supplied by a few limited foreign power semiconductor suppliers. Therefore, a large portion of technology in the power industry is dependent on other advanced countries.

In this regard, to independently build power IGBT devices and the relevant power module technology, Korean government will initiate a new 5-year project 'Power IT,' which also aims at booming the business of the power semiconductor and the allied industries. With the success of this power IT project, it is expected that the power semiconductor technology will be a basis to foster the high power semiconductor industry and moreover, there will be more innovative developments in the Korea region and globally. Also, forming the channel between the customers and suppliers, it is possible to effectively develop the customized power products, which could strengthen the competitiveness of Korean power industry.

Furthermore, the power industry including semiconductor manufacturers will be technologically self-supporting and be able to obtain good business opportunities, and eventually increase the share in the growing power semiconductor market, which could be positioned as a major industry in Korea.

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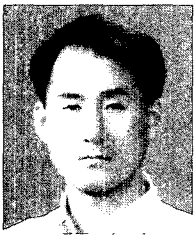

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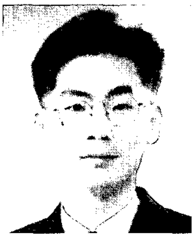

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