# MITSUBISHI ELECTRIC

# UNINTERRUPTIBLE POWER SUPPLY SYSTEMS

# INSULATED GATE BIPOLAR TRANSISTOR
# - IGBT TECHNICAL PAPER

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## 1. Introduction

The second half of the 20th century saw the birth of power electronics, which has rapidly taken an important position in the infrastructure supporting all business sectors today. Technological progress of power devices through the latter half of the 20th century and continuing through the 21st century has a close relationship with their market needs. That is, they are always required to be less noisy, more efficient, smaller and lighter, more advanced in function, more accurate, and larger in capacity. In order to meet these needs precisely, Mitsubishi Electric as a manufacturer of power devices, constantly accelerates the improvement of its existing devices and the research and development of new devices. Mitsubishi Electric power electronic equipment development and design is directly geared to making full use and optimizing power device characteristics, specification and operation capabilities. With this power device in depth knowledge and total integration of equipment components and control technology, Mitsubishi Electric can continuously provide power electronic equipment and products that will combine the very highest performance and reliability, and continually satisfy the ever expanding stringent market demands.

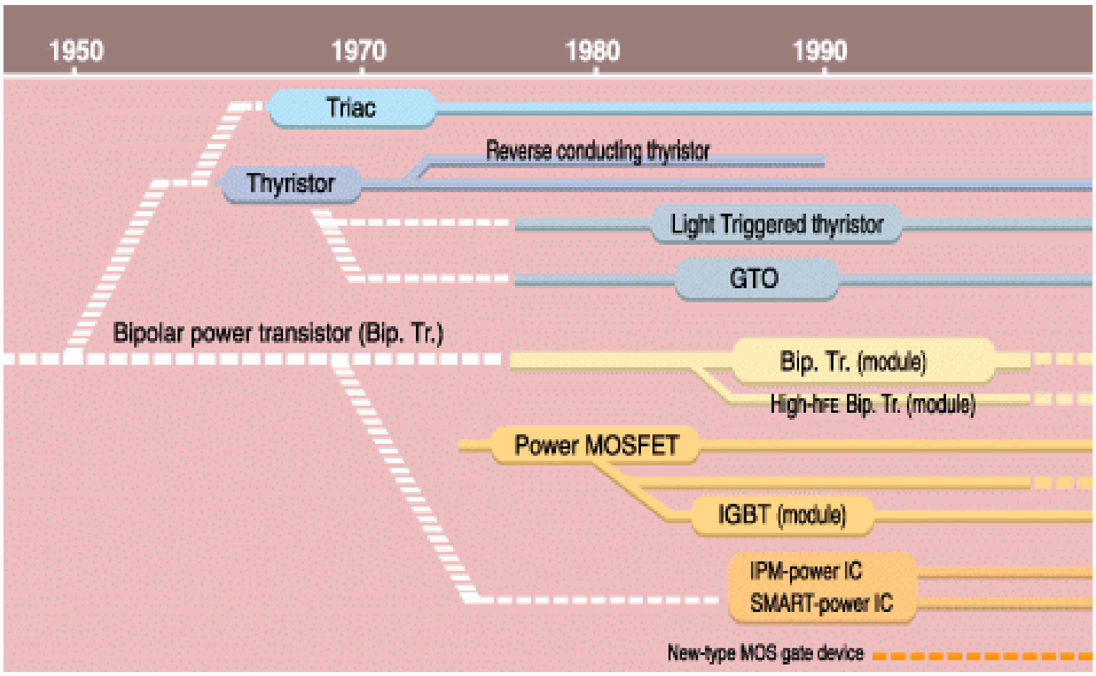
One such power electronic product that benefits from the adoption of the latest power device and control technology is the Mitsubishi Electric Uninterruptible Power Supply (UPS). UPS have become indispensable as highly reliable sources of power for the computer and communication equipment on which our increasingly information orientated society depends. The following technical paper looks at the latest power device and power conversion technology utilized in the Mitsubishi Electric series of UPS products available to meet today's market needs.

Firstly, the technological advancement of power devices and their application to the Mitsubishi Electric UPS equipment will be looked at. Following this, an understanding of the trend of UPS system, power device and control needs, power device structural composition, characteristics and operation and also UPS control technology shall be formed to realize the driving factors behind such technological advancement and change. Technological advancement for power devices and control technology utilized in the power conversion circuitry in both the UPS converter and inverter sections shall then be investigated, with advantages and disadvantages for each power device derived. The result shows the emergence of the Insulated Gate Bipolar Transistor (IGBT) as the most advanced power device to offer superior UPS performance and reliability. Details of the advancement in IGBT technology is then investigated, showing the most advanced IGBT Generation applied to the latest line of Mitsubishi Electric UPS products.

## 2. Power Device Advancement

Figure 1. shows the market trend for power device technological advancement and the adoption and introduction of the latest power device technology for the Mitsubishi Electric UPS (Related to both Converter and Inverter sections). Technological advancement being driven in response to the ever advancing system needs for improved performance and reliability (less noise, more efficient, smaller and lighter – miniaturization, more functionality, more accurate, larger in capacity).

**Figure 1.**
**Technological Advancement of Power Devices**




| | Mitsubishi Electric UPS Introduction | | | |
|---|---|---|---|---|
| **UPS Circuit** | 1964 | 1975 | 1982 | 1986 |
| **Converter** | Diode (6 Pulse) | Thyristor (6 Pulse) | Thyristor (12 Pulse) | Thyristor (12 Pulse) |
| **Inverter** | Thyristor (Commutated) | Thyristor (Improved Commutation) | Bi-Polar Transistor | MOSFET |

| **UPS Circuit** | 1987 | 1991 | 1992 | 1996 |
|---|---|---|---|---|
| **Converter** | Thyristor (12 Pulse) | Thyristor (12 Pulse) | IGBT | IGBT (DDC*) |
| **Inverter** | Bi-MOS (Combination of Bi-Polar Transistor and MOSFET) | IGBT | IGBT | IGBT (DDC*) |

* DDC: Direct Digital Control

**Note:** Figure 1. highlights the advancement in power device technology applied to the Mitsubishi UPS product from a general standpoint. The trend shows the emergence of the

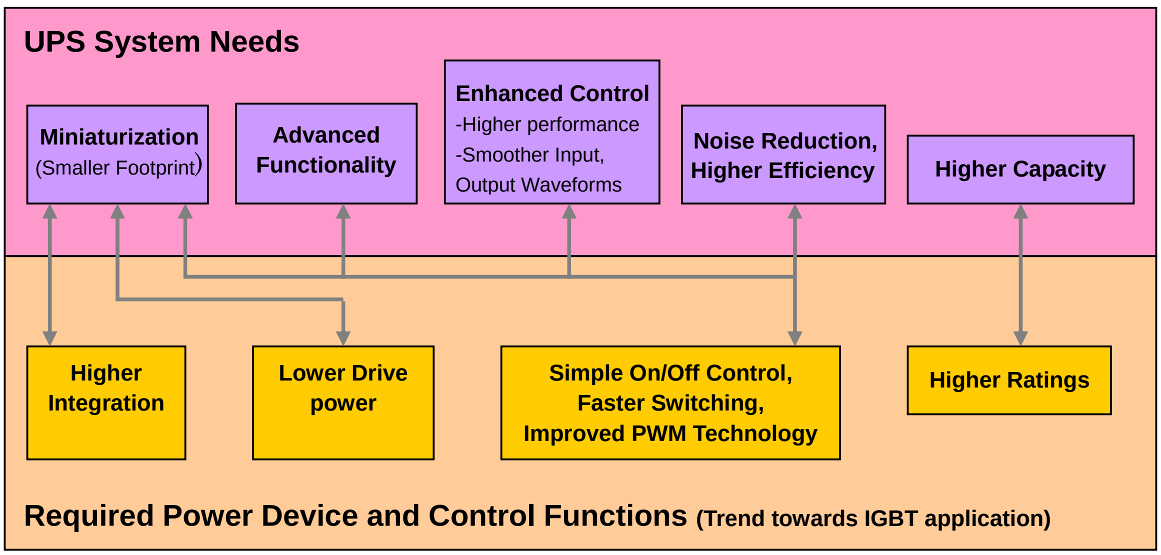
IGBT as the key power device utilized within Mitsubishi Electric UPS Modules. Later, after forming an understanding of the IGBT module, we shall look at the advancement and development of the IGBT design, and indeed the IGBT Generation applied in the current Mitsubishi Electric UPS product series (Mainly focused on the UPS product range for the Japanese and North/Latin American market).

Understanding the reasons behind the advancement of UPS power device technology can be gained by knowledge of the UPS system, power device and control requirements that drove change, some knowledge of the structural composition, characteristics and indeed operation and associated performance of the power devices listed previously in Figure.1, and also the control technology utilized for the UPS converter and inverter sections. The following sections shall focus on these three areas of discussion, all being integral to the advancement of UPS performance and reliability.

## 2.1 UPS System, Power Device and Control Needs

Figure 2. shows the relationship between the UPS system, power device and control needs establishing the trend towards IGBT application.

**Figure. 2**
**UPS System, Power Device and Control Needs**




## 2.2 Power Device Characteristics

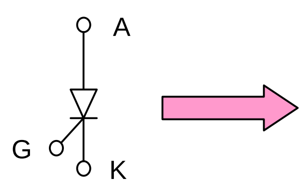
Detailed explanation of the structural composition of semiconductor components is complicated and difficult to understand unless considerably knowledgeable in this field. The following information is intended to try and give the reader a minimum understanding that is required to grasp the reasons behind UPS technology change, however a minimum knowledge related to semiconductor device composition and operation is assumed.

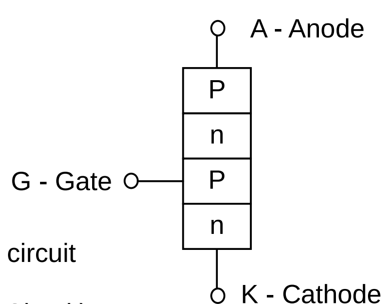
### 2.2.1 Thyristor (Silicon Controlled Rectifier - SCR)

The thyristor can be described as one of the most important power semiconductor devices, being responsible for the initial capability and generation of power conversion electronic equipment such as UPS. Thyristors have been and still are used extensively in power electronic circuits within many applications, including some UPS products available in today's market (As seen in Figure 1. Mitsubishi Electric no longer utilize thyristor technology for UPS products). A thyristor is a four layer semiconductor device of alternating pnpn structure with three pn-junctions. It has three terminals: anode, cathode, and gate (control terminal). Thyristors are manufactured by diffusion. Figure 3. shows the thyristor symbol and sectional view of three pn-junctions.

The thyrsitor is a latching device having two stable states, off-state and on-state. When the anode voltage is made positive with respect to the cathode, the thyristor is forward biased and is said to be in the off-state. A thyristor is turned on by increasing the anode current. This can be accomplished in many ways, however the scope of this paper means that the most practical of applying a gate signal is described. If a thyristor is forward biased, the injection of gate current by applying a positive gate voltage between the gate and cathode terminal would turn on the thyristor. Latching current is the minimum anode current required to maintain the thyristor in the on-state, immediately after a thyristor has been turned on and the gate signal has been removed. Once a thyristor conducts, it behaves like a conducting diode and there is no control over the device. The device will continue to conduct as long as there is sufficient Holding current. Holding current is the minimum anode current to maintain the thyristor in the on-state and is less than the latching current. A thyristor which is in the on-state can only be turned off by reducing the forward current to a level below the holding current. The turn off means that the forward conduction of the thyristor has ceased and the reapplication of a positive voltage to the anode will not cause current flow without applying the gate signal. There are various techniques for turning off a thyristor, and commutation is the usual term applied. Commutation can either be natural or forced. If the source (or input) voltage is ac, the thyristor current goes through a natural zero, and a reverse voltage appears across the thyristor. The device is then automatically turned off due to the natural behavior of the source voltage. This is known as natural commutation. In some thyristor circuits, the input voltage is dc (UPS inverter) and the forward current of the thyristor is forced to zero by additional circuitry called a commutation circuit to turn off the thyristor. This technique is called forced commutation.

**Figure 3.**
**<u>Thyristor Symbol and Sectional View</u>**




- ■ Simple and Reliable On control (Gate) circuit
- ■ Low on state drop
- □ No off Control (Need for Commutation Circuit)
- □ Slow Switching

| ■ Advantage □ Disadvantage |
|---|

The introduction of power transistors and indeed MOS technology into the process area of power semiconductors has created revolutionary device and application advantages. We shall look at the application advantages in more detail in the next section, however it can be seen from the above thyristor off control limitations that the thyristor has definite disadvantages when applied to UPS inverter sections (Requirement of forced commutation circuitry). As can be seen previously from Figure 1., Power transistors effectively replaced the use of thyristors in the Mitsubishi Electric UPS inverter section from 1982, and indeed with the development of the IGBT power device, from 1992 also brought an end to the use of thyristors in the converter section. Again we shall look at the benefits of such change in the following section.

### 2.2.2 Power Transistors and MOS Technology

Power transistors have controlled turn-on and turn-off characteristics and are therefore used as switching elements. The switching speed of modern transistors being much higher than that of thyristors. In this paper, the three major power device technologies shall be discussed:

1.) Bi-polar junction transistors (BJTs)
2.) Metal-oxide-semiconductor field-effect transistors (MOSFETs)
3.) Insulated-gate bipolar transistors (IGBTs)

In addition, the goal of this paper is to focus mainly on and understand the IGBT power device. Therefore the following information will be explained in relation to IGBT detail.

#### 2.2.2.1 Structure and Operation of IGBT Module

The IGBT, Insulated Gate Bipolar Transistor, is a switching transistor that is controlled by voltage applied to the gate terminal. Device operation and structure are similar to those of an Insulated Gate Field Effect Transistor, more commonly known as a MOSFET. The principal difference between the two device types is that the IGBT uses conductivity modulation to reduce on-state conduction losses (Conductivity modulation is the optimization of the MOSFET component of the IGBT so device characteristics feature high speed, low voltage drop and efficient silicon utilization.) A brief comparison between the structures of the IGBT, MOSFET and npn Bipolar Junction Transistor (BJT) is depicted in Figure 4. Device symbols are also shown. The npn BJT is a three junction device that requires a continuous current flowing into the base region to supply enough charges to allow the junctions to conduct current. Because the MOSFET and the IGBT are voltage-controlled devices, they only require voltage on the gate to maintain conduction through the device. The IGBT has one junction more than the MOSFET, and this junction allows higher blocking voltage and conductivity modulation during conduction. This additional junction in the IGBT does however limit its switching frequency in comparison to the MOSFET.

##### 2.2.2.1.1 IGBT Silicon Structure

The IGBT silicon structure is as shown in Figure 5. A positive voltage on the gate attracts electrons from the “p” gate region towards the silicon surface under the gate. These electrons invert the “p” directly under the gate to form an “n” region, thus creating a path for charge flow between the “n” collector region and the “n” emitter region. A zero or negative voltage (depends on the device) on the gate maintains the off-bias.

IGBT wafer processing is similar to FET processing. The silicon material is a dual epitaxial structure, and gate and emitter regions are diffused and/or ion implanted into the emitter side. Selective doping, electronic irradiation, and other processing techniques are used during emitter-side processing.

**Figure. 4**
**Three Major Device Technologies**

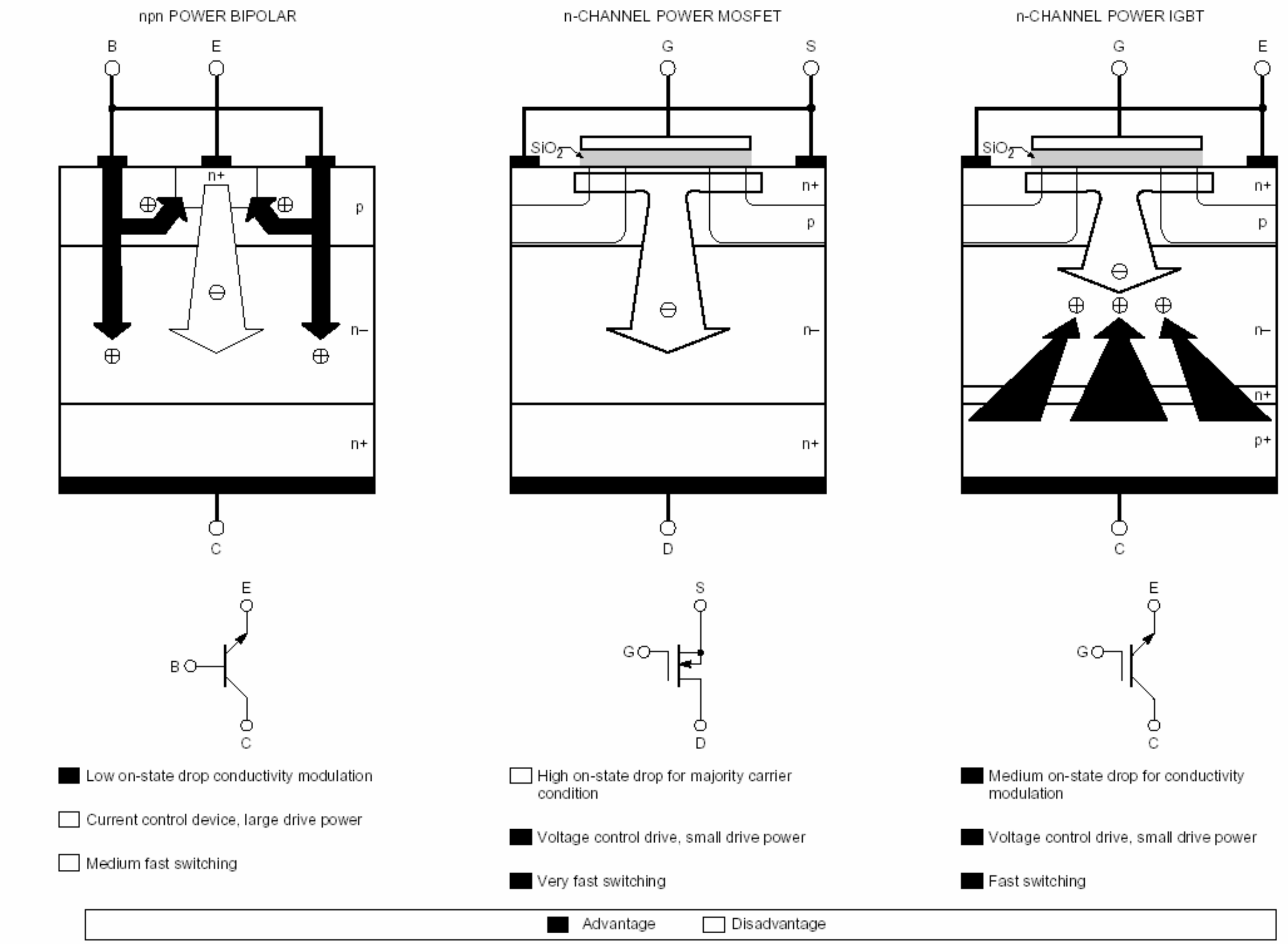
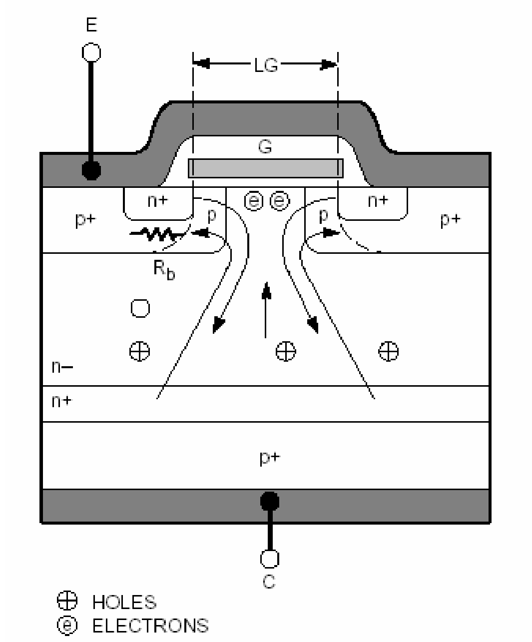



**Figure. 5**
**IGBT Cross Section and Silicon Structure**



#### 2.2.2.1.2 IGBT Device Operation

When the device is on, the collector is at a higher voltage than the emitter, and therefore minority carriers are injected from the collector p+ region into the collector bulk region (n+ buffer layer and collector “n” region). The charges reduce the collector bulk region resistance and thus collector to emitter voltage drop is reduced. When a positive gate voltage is first applied, a gate current flows until the gate capacitance is charged and the gate voltage rises to the “on” level. When the gate voltage is removed, the charges injected into the collector bulk region must be removed before high voltage can be blocked.

#### 2.2.2.1.3 Switching and Conduction Losses

Switching Loss is the power dissipated during the turn-on and turn-off switching of transistors. Conduction losses (or On state drop) are the losses that occur while the transistor is on and conducting current. In high frequency Pulse Width Modulation (PWM) control and switching, switching losses can be substantial and must be considered during design.

## 2.3 UPS Control Circuitry – Direct Digital Control (DDC) and Pulse Width Modulation (PWM) Technique

In addition to the utilization of high performance IGBT modules, control circuit technology and technique is also an important consideration when analyzing UPS inverter and converter section performance, and understanding the advancement in power device technology within the UPS application. The advancement and evolution through to the IGBT power device has also enabled the same apparent advancement in control technology and indeed control capability. It is not the scope of this paper to give an in depth detailed account of the control and Pulse Width Modulation (PWM) techniques utilized by the Mitsubishi Electric UPS control circuitry, however the fundamental benefits achieved by using the latest state of the art control techniques should be understood.

The Mitsubishi Electric UPS Module control circuitry utilizes Digital Signal Processor (DSP) and Application Specified IC (ASIC) which create advanced controllability and simplify the control circuit. Direct Digital Control (DDC) utilizing DSP and ASIC ensures high reliability, as well as superior functionality and performance. From Figure 1. it can be seen that full DDC IGBT control for both inverter and converter sections was introduced to the Mitsubishi Electric UPS products from 1996. Each UPS Module inverter utilizes unique Major and Minor Feed Forward Current Loop Control, enabling instantaneous control of UPS Module output. The digitalized UPS Module incorporates Field Programmable Gate Array (FPGA) for Current Minor Loop Control, and DSP based control for Feed Forward Control and Voltage Major Loop Control. The UPS Module inverter and converter utilizes state of the art new improved Pulse Width Modulation (PWM) to control the IGBT power devices. The DSP calculates the inverter/converter voltage reference and outputs it to the FPGA where comparison to a carrier waveform is performed. From this comparison IGBT switching (Turn on/off) timing is generated. Mitsubishi Electric UPS series utilize different PWM technique (and switching frequencies) depending on when the product was first introduced, what IGBT Generation power device is used (refer to following section for details), and also the specific design criteria for the UPS module (High efficiency UPS requirement etc.). With DSP and DDC, typical control within the range of 200 to 500 samples per cycle is possible. The associated benefits for this new improved PWM control and higher speed switching capabilities of IGBT power devices enables greatly enhanced control performance for both inverter and converter sections, reduced audible noise, better efficiency and miniaturization of UPS circuits.

The following section looks at the UPS inverter and converter sections in more detail.

## 3. UPS Inverter and Converter Section Power Device Application

Now that a basic understanding of the UPS system, power device and control needs, power device characteristics, performance and operation and also the UPS control technology has been achieved, the specific advantages and disadvantages related to power device application within UPS power conversion sections can be more easily realized.

It was seen that devices such as BJTs and thyristors require complicated and very inefficient methods of driving the device due to their low gain and minority carrier device characteristics. In addition, thyristors become difficult to control due to the loss of gate control during turn-off. MOSFETS have simple gate drive requirements, being driven with low power, voltage pulses of required polarity. This simplifies the circuit design and the switching characteristics can be accurately controlled if all of the circuit parameters are well known. However, the demands for power converters are not fully satisfied by power Bi-Polar transistors (BJTs) and power MOSFETS. High current and high voltage BJTs are available, but their switching speeds are not satisfactory. Power MOSFETS have high speed switching, but high voltage and high current modules are not available. The IGBT device is a power semiconductor device introduced to overcome the limitations of the power BJTs and power MOSFETS. This device eliminates the high on-state losses of the MOSFET while maintaining the simple low-power, voltage driven gate drive requirements of that device. This device is controlled by the gate voltage as is the power MOSFET, but the output current is that of a Bipolar transistor. The IGBT device combines the best features of both the Bipolar transistors and of the MOSFET.

### 3.1 UPS Inverter Application

It has been seen that a power transistor is much simpler and efficient than a forced thyristor commutation switch, and the limitations of the thyristor for UPS inverter applications become obviously apparent. The following evolution through the utilization of power BJT and MOSFET to the superior inverter characteristics and performance achieved by utilizing IGBT power devices and improved PWM inverter control techniques can be easily realized. Typical fast switching capabilities and simple control of the IGBT device, and also high frequency and improved PWM control techniques enable excellent UPS inverter output specification and performance (High DSP PWM control sample rate per cycle, low output voltage distortion, cleaner output voltage waveforms - smaller output filter requirement, and instantaneous transient response * See note), low audible noise, smaller inverter footprint and of course high reliability.

* **Note:** The deviation of the inverter output voltage from a true sine wave can be measured as the output voltage total harmonic distortion (THD). An output AC filter is required to reduce this distortion to an acceptable level. The AC filter size is determined not only by the amount of unwanted harmonics in the inverter output but also by the frequencies of these harmonics. The lower the harmonic frequencies generated by the inverter, the larger will be the AC filter. Consequently, if lower frequencies in the inverter waveform (third, fifth or greater harmonics) can be reduced in magnitude or eliminated, the AC filter size can be made smaller. For IGBT PWM inverter control, harmonics are easily restricted to the higher frequencies, with lower order harmonics eliminated. A smaller (lower impedance) filter results in improved output voltage regulation (particularly transient regulation) and less load induced harmonic distortion of the output voltage. This leads to better load compatibility.

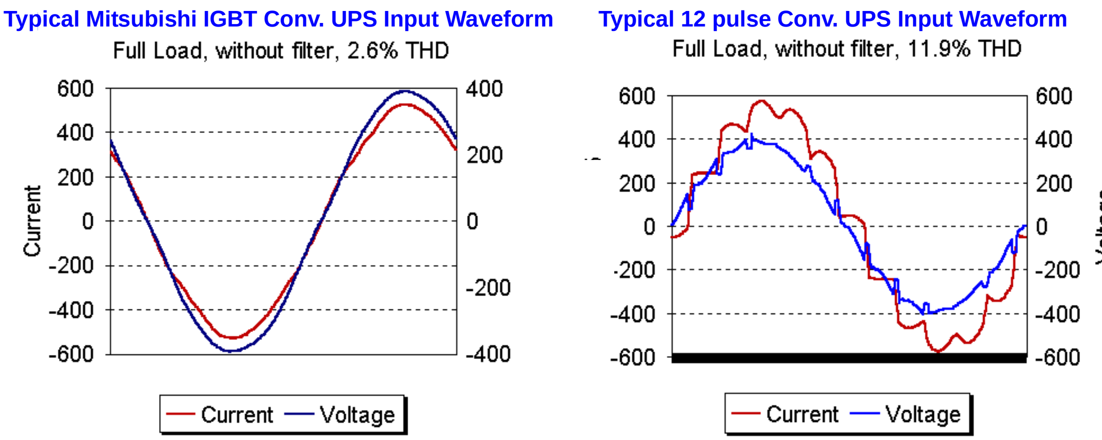
### 3.2 UPS Converter Application

While the UPS inverter section has evolved several times over the last few decades, the use of thyristors in the converter section is still being used among many UPS products available today. In addition it has only been within the last decade that the thyristor was replaced in Mitsubishi Electric UPS products due to the advancement of IGBT and PWM control technology. The thyristor is more suited to the converter and rectifier section of the UPS due to natural commutation. The device being automatically turned off due to the natural behavior of the source voltage. However there are several specific negative aspects that arise when applying thyristors in UPS converter sections:

Perhaps the single most important negative aspect of the thyristor application within the converter section is the inherently high level of reflected input current total harmonic distortion (THD). THD was briefly mentioned in the previous section in relation to the inverter output voltage waveform. THD is defined as the measure of closeness in shape between a waveform and its fundamental component (the deviation from a perfect smooth/clean sine wave).

Typical input current THD is 12% at 100% load for a 12-Pulse rectifier, and typically 30% at 100% load for a 6-Pulse rectifier applied to a UPS converter section (Without additional harmonic filters). To generate 12-Pulse rectification, a delta/star transformer is used to provide 30 degree phase shift of the input phases and an extra 6-pulse rectifier circuit is added, generating 12-Pulse or rectification stages during one cycle. Due to this additional cost and space requirement for 12-pulse rectification, 6-pulse rectifiers have become typical standards, which brings about the need for additional filter circuitry on UPS inputs to reduce the input current THD or expose the utility or possible generator supply to severe harmonic feedback content (6-pulse or thyristor rectification control stages produces a very crude step sine wave that requires filters to try and produce a smoother, cleaner waveform with no distortion). Typical consequences of high harmonic feedback being high voltage distortion and overheating of transformers or generator alternators. These adverse consequences leads to the use of the resonant LC filter that is tuned to a specific frequency (Typically the 11th harmonic in 12-pulse rectifiers and the 5th harmonic in 6-pulse rectifiers). These harmonic filters reduce the input current THD levels to between 5% and 10% of the fundamental at full load only, but deteriorate at lower load levels. The need for additional input harmonic filters improves the input current THD, however also introduces further negative aspects to the overall system. Of course additional space and cost will be required for the filters and overall system efficiency shall be reduced, however a more critical shortcoming is the possible incompatibility with the generator (especially on low UPS load conditions when harmonic filters with large capacitance circuits are utilized). A typical solution to this problem is to remove such filters during low loading conditions, however the original reason for having the filter is then defeated and other negative and undesirable effects to the generator becoming apparent (for example heat spots due to equivalent negative phase sequence current flow – details are out of scope of this paper). The introduction of the transistorized and indeed IGBT converter offers considerably low input current THD, and therefore eliminates the need for additional input harmonic filters and any associated problems with them. IGBT converters have an input current specification of typically 3% maximum THD at 100% load, and 5% Maximum THD at 50% load (High DSP PWM control sample rate per cycle, typically of within the range of 200 to 500 samples per cycle, enables a very accurate and smooth, clean sine wave to be produced with low distortion - without the need for additional harmonic filters). Figure 6. shows a typical input waveform comparison between a Mitsubishi UPS with IGBT Applied converter and a typical UPS with a 12 Pulse applied Converter section (Without any additional input harmonic filters):

**Figure 6.**
**<u>IGBT and 12 Pulse Converter Input Waveforms</u>**




In addition to this low THD specification, an additional important benefit obtained with the utilization of IGBT in the converter section is that high input power factor is achieved. With the high controllability and switching capability of the IGBT device, together with PWM control technology, the phase of the input current and voltage can be made the same and so input power factor can be controlled to near unity. This high power factor allows a lower input kVA requirement, which in turn with the lower input current THD specifications allows an approximate equivalent generator rating requirement and sizing characteristic (Mitsubishi Electric IGBT converter technology generator rating ratio is 1:1, that is to say the kW rating or power consumption of the generator is equal to the kVA rating of the UPS). It is common practice that for thyristor based converter technology (whether 6-pulse or 12-pulse), a certain amount of over-sizing for generator rating or generator power usage is required. In some cases, doubling of generator rating is not uncommon.

An additional advantageous feature of the IGBT converter, PWM and control utilized within Mitsubishi Electric UPS is that the converter output and DC link voltage can be controlled during transient response and severe step load conditions. The DC Link voltage is controlled so has never to drop to the minimum nominal voltage level that would cause battery discharge. Therefore the battery is never cycled during step load conditions. Traditional thyristor converter and control methods cycle the battery under 100% step load changes resulting in reduced battery life.

Figures 7. and 8. show a detailed account of the advantages and disadvantages of power devices and their control capabilities when applied to UPS inverter and converter sections, giving the reader an understanding of the reasons that drove Mitsubishi Electric UPS technological advancement and change.

Other advantages of the IGBT technology in relation to the power device characteristics are not as obvious. The main focus in this section relates specifically to the overall advantages and disadvantages when IGBT are applied in UPS inverter and converter sections. The following section looks at the IGBT device in more detail, and gives information regarding more intricate characteristics of the IGBT.

## Figure 7. UPS Inverter Power Device Application

| | Thyristor | Bi-Polar Transistor | MOSFET | IGBT |
|---|---|---|---|---|
| **ADVANTAGES** | ■**Simple and Reliable On Control (Gate) Circuit**<br>■**High current capabilities**<br>-High inverter power capabilities<br><br>Technological Advancement → | ■**On/Off Control**<br>■**Medium switching Speed**<br>-Improved control, PWM<br>-Improved inverter performance and specification<br>-Improved Output Voltage waveform, THD<br>-Minitiarization of output filter<br>■**Low On state Drop**<br>-Low Heat Dissipation, Low conduction losses<br>■**High Current Capacity**<br>-High inverter power capabilities<br><br>Technological Advancement → | ■**On/Off Control**<br>■**Very Fast Switching Speed**<br>-PWM control<br>-High inverter performance and specification<br>-Clean Output Voltage waveform, Low THD<br>-Minitiarization of output filter<br>■**Small Drive Power (Voltage drive)**<br>-Simple Drive circuit<br>-high reliability<br>-Low power consumption<br>■**Low Audible Noise**<br>-Noiseless inverter<br>■**Small size** (inverter footprint reduced)<br><br>Technological Advancement → | ■**On/Off Control**<br>■**Fast Switching Speed**<br>-New Improved PWM inverter control<br>-High inverter performance and specification<br>-Clean Output Voltage waveform, Low THD<br>-Minitiarization of output filter<br>■**Low Audible Noise**<br>-Noiseless inverter<br>■**Medium On State Drop**<br>-Low Heat Dissipation, Low conduction Losses<br>■**Small Drive Power (Voltage drive)**<br>-Simple drive control circuit<br>-Simple Control, Less components, high reliability<br>-Low power consumption<br>■**High current/Voltage Capacity**<br>■**Higher Inverter Efficiency**<br>(Switching Frequency kHz dependent – see below)<br>■**One piece package integration design**<br>-Minitiarization<br>■**Small size** (inverter footprint reduced) |
| **DISADVANTAGES** | ☐**Slow Switching**<br>-Poor control, inverter Performance and output specification<br>-Poor Output Voltage Regulation during transient load conditions<br>-Poor Output Voltage waveform, High Output Voltage THD<br>-Large Output Filters required<br>☐**Difficulty to Control Off (Need for Commutation Circuit)**<br>*The need for Commutation circuit causes:*<br>-Increased inverter size, parts count, Increased Cost<br>-Lowers Reliability<br>-Increased audible noise<br>-Power consumption, decreases overall efficiency<br>☐**High Switching Noise**<br>☐**High Audible Noise**<br>☐**Low Overall Inverter efficiency**<br>☐**High Operating Costs** | ☐**High Audible Noise**<br>(lower than thyristor)<br>☐**Large Drive Power (Current drive)**<br>-Complicated drive control circuit<br>-Large power consumption<br>-More components, Less reliability | ☐**High on State Drop**<br>-High Heat Dissipation, High conduction Losses<br>-Lower Efficiency<br>☐**Low current Capacity**<br>-Limited inverter power capabilities | ☐**The higher the switching frequency (kHZ), the more switching loss.**<br><br>**Note**: In high frequency PWM switching losses can be substantial and must be considered during design. |

**Figure 8. UPS Converter Power Device Application**

| | Thyristor | Bi-Polar Transistor | MOSFET | IGBT |
|---|---|---|---|---|
| **ADVANTAGES** | ■**Simple and Reliable On (Gate) Circuit**<br>■**Self Commutating (Natural off control)**<br>■**High current capabilities**<br>-High converter power capabilities | **N/A** | **N/A** | ■**On/Off Control**<br>■**Fast Switching Speed**<br>-New Improved PWM control, High converter performance and specification<br>■**Low input current THD**<br>-Typically 3% Max. at 100% Load, 5% Max at 50% Load.<br>-No need for additional harmonic filters<br>■**Power Factor Control**<br>-Near unity (1.0) power factor can be achieved<br>■**1:1.1 Generator Rating**<br>-No Over-sizing of Generator rating requirement<br>■**No Battery Cycle during 100% Step Loads** – Battery Longevity<br>■**Low Audible Noise**<br>■**Medium On State Drop**<br>-Low Heat Dissipation, Low conduction Losses<br>■**Small Drive Power (Voltage drive)**<br>-Simple drive control circuit<br>-Simple Control, Less components, high reliability<br>-Low power consumption<br>■**High current/Voltage Capacity**<br>■**One piece package integration design**<br>-Minitiarization<br>■**Small size** (inverter footprint reduced) |
| **DISADVANTAGES** | ☐**Slow Switching**<br>-Poor control, converter Performance and input specification<br>☐**High Converter Input current THD:**<br>-6 Pulse Typically 30% THD (Lowest cost rectifier circuit)<br>-12 Pulse Typically 12% THD [without additional input filters]<br>-High THD feedback to utility<br>☐**Need for additional Input harmonic filters to reduce THD**<br>-Additional space and cost.<br>-Generator compatibility problems on low loads<br>-Reduction in overall efficiency<br>☐**No Power Factor Control**<br>-Typically 0.7 to 0.8. - Larger input kVA requirement<br>☐**Generator rating requirement Over-sizing**<br>-required due to high input THD and larger kVA requirement<br>☐**Battery cycled during 100% Step Load**<br>-Reduced Battery life<br>☐**Switching Noise**<br>☐**High Audible Noise** | **N/A** | **N/A** | ☐**The higher the switching frequency (kHZ), the more switching loss.**<br>Note: Switching Loss is the power dissipated during the turn-on and turn-off switching of transistors. In high frequency PWM switching losses can be substantial and must be considered during design. |

Technological Advancement →

# 4. IGBT Development and Advancement

It was shown earlier the advancement of semiconductor power device technology in relation to UPS power conversion circuit application. The IGBT emerged as the key power device utilized within today's Mitsubishi Electric UPS products to offer the highest performance, quality and reliability. It is important to also understand that the IGBT power device itself has advanced in performance and specification since its initial introduction (First and Second Generation IGBT) in the early 1990s. Mitsubishi Electric through a process of continuous improvement and new development strategy designed to meet existing and future customer requirements developed and introduced the Mitsubishi Third Generation IGBT to the market in the 4th quarter of 1992. The early 3$^{rd}$ Generation IGBT Module package were called H series, with a new IGBT module package called "U-Series" developed (from the H-Series process) and introduced in 1996. The 3rd Generation of IGBT is now in widespread use within today's market products, with the IGBT H series being a key and prominent device utilized within many UPS products on offer. Mitsubishi Electric however no longer utilize the H-Series Module, having advanced to U-Series application. In addition Mitsubishi Electric have since introduced the 4$^{th}$ Generation IGBT device, and utilizes this technology as well as the 3$^{rd}$ Generation IGBT U series in their latest UPS Series product range. The following explains the benefits and reasons behind IGBT Generation advancement, and also looks at the IGBT Generation applied in the current Mitsubishi Electric UPS product series.

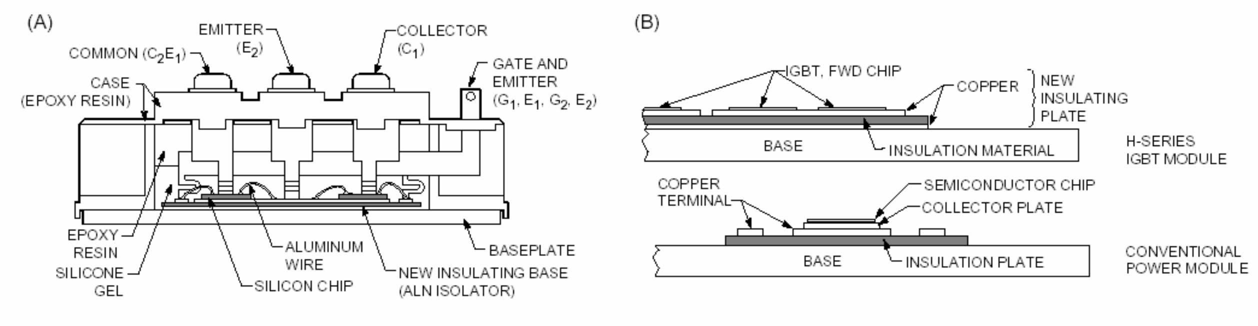
## 4.1 IGBT Generations

The 3$^{rd}$ Generation IGBT module realized significantly improved switching and conduction losses over second generation devices. The on-state voltage was lowered by using advanced processing techniques such as shallow diffusion, reduced cell size, and optimized layout. In order to further reduce switching losses, a new free-wheel diode was developed for the 3$^{rd}$ Generation of IGBT module. In order to understand the advancement from the original H series 3$^{rd}$ Generation IGBT package to the U series package, and also to the latest 4$^{th}$ Generation IGBT package, a more in depth structural knowledge and understanding of the IGBT device is required.

### 4.1.1 IGBT Module Packaging Construction and Layout

IGBT Modules consist of multiple IGBT chips mounted on an isolated substrate, which is itself mounted on a heat-sinking copper base-plate. Refer to Figure 9A. Mitsubishi IGBT Modules use an isolating ceramic substrate with copper patterns metallurgically bonded to the top and bottom surfaces. Refer to Figure 9B. This mounting method allows highly automated module assembly while minimizing thermal impedance. Mitsubishi IGBT modules use materials with similar thermal coefficients of expansion so that thermal stress is limited. As a result these IGBT modules can be expected to provide improved thermal life cycle expectation over existing power transistor modules. Free-wheeling diodes are also mounted in the module for ease of system assembly and to allow minimum lead inductance, both inside and outside the module (lower inductance offers simplified power circuit and snubber circuit designs). Interconnection inside the modules is accomplished with rigid bussing to ease assembly. Rigid bussing also offers symmetric layout of internal components so the parasitic inductance is reduced and module ruggedness is enhanced.

**Figure 9.**
**Structure of Mitsubishi IGBT Module and Module Base Plate Construction**




### 4.1.2 Features of 3rd Generation U-Series IGBT Packages

The U-Series package technology achieves a significant reduction in internal inductance and improved reliability and switching operation over older designs. The time required to assemble the U-Series module is substantially reduced by using a special case that has the power electrodes molded into its sides rather than inserted after the case is molded. Figure 10. is a cross section drawing of the U-Series IGBT module package. The main electrodes are connected directly to the power chips using large diameter aluminum bonding wires. In order to help simplify power circuit and snubber circuit designs or possibly eliminate them altogether an effort was made to minimize inductance of the U-series package. A variety of techniques were used to reduce each component of the package inductance. One of the most significant improvements was made possible by the insert molded case design. Wide electrodes are molded into the side of the case to form parallel plate structures that have considerably less inductance than H-Series electrodes. In addition, the strain relieving “S” bends that were needed in the electrodes of H-Series modules are not needed in the U-series package because the aluminum bond wires perform the strain relieving function. Elimination of these “S” bends helped to further reduce the electrode inductance. Overall, as a result of these inductance reducing features the U-series modules typically have about one third the inductance of H-Series modules. A further reduction in assembly line time was achieved by reducing the number of soldering steps during manufacturing. With the H-Series module the chip to substrate and substrate to base plate soldering is done first with high temperature solder. Then the case is attached to the base plate and a second low temperature soldering step is used to connect the power modules. In the U-series module the second step is not needed because the connections to the power electrodes are made using the aluminum bond wires. The soldering temperature of the chip and substrate attachment can be reduced. The result is a reduction in thermal stress during manufacturing and improved power cycle reliability.

Figure 11. shows the structural difference, improvement of switching operation waveform and the overall advantages of the IGBT U-Series Module over the H-Series Module.

**Figure 10.**
**Cross Section of U-Series Module Package**

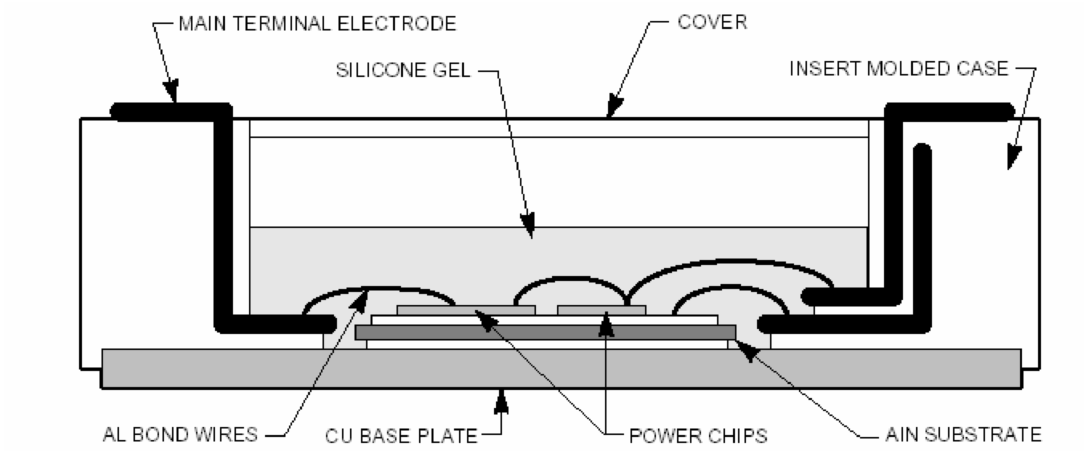
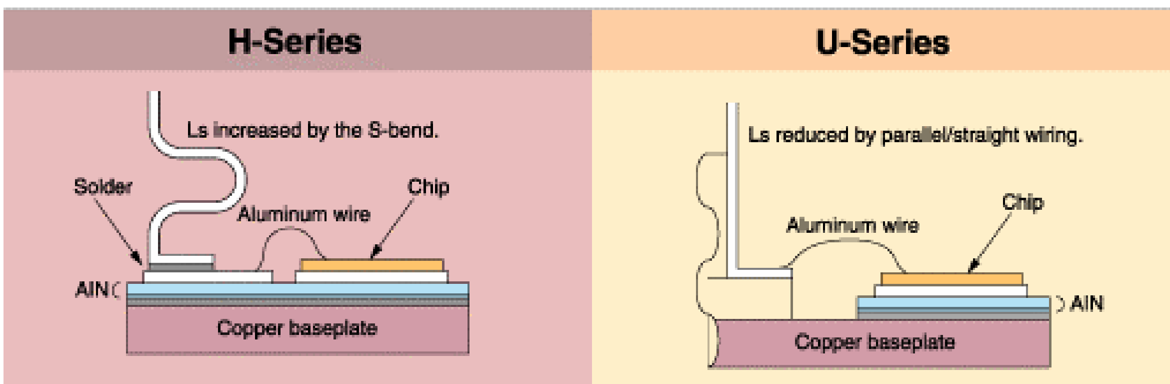
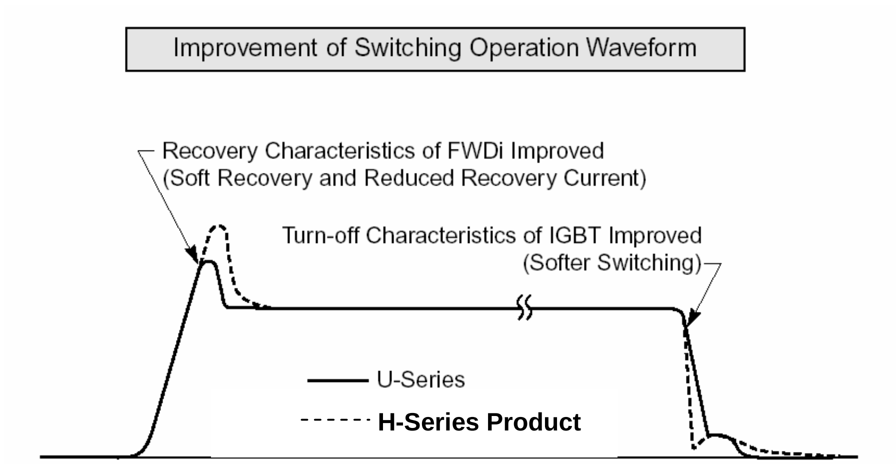



**Figure 11.**
**U-Series Module and H-Series Module Package Comparison**



| U-Series IGBT Module | Advantages |
|---|---|
| ■ **New Structure Package**<br><br>◆ Optimization of Insulating substrate<br>◆ Structural Improvements of internal electrodes<br>◆ SLP (Solderless package) structure | **-General**<br>-Improved Reliability<br>-Improved Switching Operation<br>-Reduced internal Inductance, Reduction of Insulation capacitance<br>-Reduced manufacturing process time.<br>-Decrease of Switching Surge Voltage<br>-Elimination of Voltage and Current Oscillation when Switching<br>-High Level Integration -> Reduced Size and Weight<br>-**Insulating-substrate optimizing**<br>-High-temperature thermal conductivity improved -> to reduce thermal resistance, improved thermal performance<br>-Improved Ruggedness to Mounting Stresses<br>-Reduction of Insulation Capacitance -> Reduction of Noise current in Heat sink<br>-Cooling fins reduced in the degree of flatness -> More compact<br>**Structural Improvement of internal electrodes**<br>-Low inductance (Ls) is achieved -> simplify power circuit and snubber circuit designs or possibly eliminate them altogether. U-series modules typically have about one third the inductance of H-Series modules. Increased Reliability.<br>**SLP (Solderless package) structure**<br>-High Reliability -> Higher Mean Time Between failures (MTBF)<br>-Reduced manufacturing process time<br>- Reduction in thermal stress during manufacturing and improved power cycle reliability. |
| ■ **Improved IGBT and FWDi (Free Wheeling Diode) Chip Characteristics** | -Soft Switching -> Reduced switching loss<br>-Recovery Characteristics of FWDi improved -> Soft Recovery and Reduced Recovery Current, reduced switching loss<br>-Turn off characteristics of IGBT improved -> soft switching -> less switching loss<br>-Power Loss reduced<br>-Reduced internal inductance of FWDi Chip -> noise reduction |
| ■ **Large Safe Operating Area (SOA)** | - High Turn off switching SOA and Short circuit SOA capabilities -> Protection against device destruction, longer life.<br>**Note:** The safe operating area (SOA) describes the capability of a transistor to withstand simultaneously significant levels of voltage and current. |

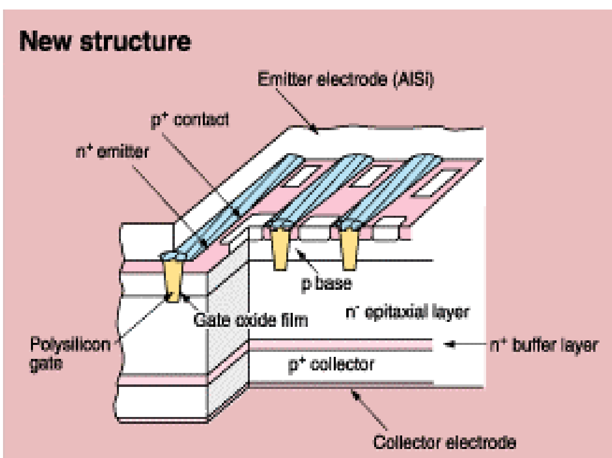
### 4.1.3 4th Generation IGBT Package

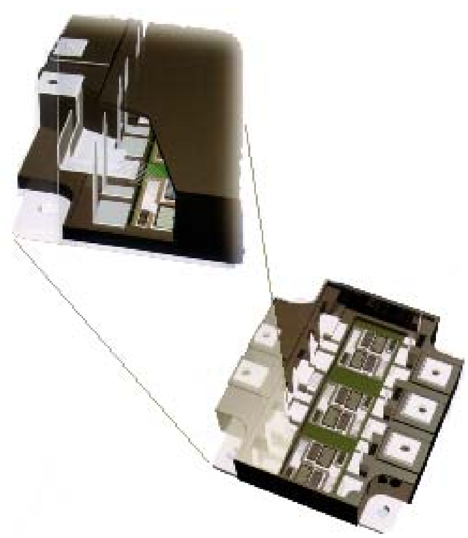
The evolution of the IGBT through the first, second, and third generations has been achieved mainly by microstructuring a chip-surface-formed MOSFET. Since it is known, however, that further microstructuring just turns out to increase the turn-on voltage, the present third generation is considered to be almost the limit. A new-type MOS gate device was developed as an IGBT that breaks through the above limit. This IGBT module has a structure in which a narrow and deep trench is formed on the surface of an IC chip and then a MOSFET is formed on the side wall of the trench. Figure 12. shows the 4th Generation Trench IGBT Unit Cell structure and the low inductance package.

The benefits of the 4th generation Trench IGBT follow on from the advances made from the H-Series to the U-Series 3rd Generation IGBT. Improvement in switching characteristics, lower turn on voltage requirements and achieving lower package inductance enable less switching losses and higher performance specification.

The following section looks at the IGBT Generation applied in the current Mitsubishi Electric UPS product series.

**Figure 12.**
**4th Generation Trench IGBT Unit Cell structure and low inductance package**



## 5. Mitsubishi Electric UPS Product IGBT Generation Application

Figure 13. shows IGBT Generation applied within the Mitsubishi Electric UPS Series Line up and also the power capabilities available (Specific to the UPS product range for the Japanese and North/Latin American market):

**Figure 13.**
**Mitsubishi Electric UPS IGBT Generation and Application**

| UPS Product Series | UPS Module Capacity Range | Converter Power Device | Inverter Power Device |
|---|---|---|---|
| **Japan** | | | |
| 9200Z | 50 ～ 1500 kVA | IGBT 3rd Gen. (U-Series) | IGBT 3rd Gen. (U-Series) |
| 9800J | 100 ～ 500 kVA | Diode/IGBT 4th Gen. * | IGBT 4th Gen. * |
| **North America** | | | |
| 9800A | 100 ～ 500 kVA (750kVA available August 2003) | Diode/IGBT 4th Gen. * | IGBT 4th Gen. * |
| 9700A | 100 ～ 225 kVA | IGBT 3rd Gen. (U-Series) | IGBT 3rd Gen. (U-Series) |
| 2033A | 30 ～ 75 kVA | IPM* | IPM* |
| 2033C | 7.5 ～ 50 kVA | IGBT 3rd Gen. (U-Series) | IGBT 3rd Gen. (U-Series) |
| 2033D (New) | 30, 50, 80 kVA | IGBT 4th Gen. | IGBT 4th Gen. |

* Diode/IGBT 4th Gen: The 9800A/J UPS Module series is specifically designed to offer a High Efficiency On Line Double Conversion UPS System solution (Up to 94% AC to AC). The Converter section utilizes a diode bridge rectifier working in conjunction with a 4th Generation IGBT Chopper/Charger and improved PWM control circuitry to offer increased efficiency, while continuing to provide high input specification and converter performance a-kin to the IGBT converter, with low input current distortion and high power factor.

* IPM: The development of the IGBT has allowed peripheral circuits to be built into the power modules in a cost effective manner. The Intelligent Power Module (IPM) includes gate drive and protective circuits within the module package, offering a more compact and miniature package. Power capability of the IPM is a limiting feature.

It can be seen that not only does Mitsubishi Electric UPS equipment incorporate the latest power device and control technology, but also applies the most advanced generation power device available. Keeping up with the technological advancement of the key power device enables Mitsubishi Electric UPS equipment to constantly offer the customer optimum product performance.

## 6. Conclusion

It has been shown in this paper that the IGBT is the key power device utilized within today's Mitsubishi Electric UPS products. The benefits shown when applying the IGBT power device to the UPS power conversion sections explain the reasons behind such technological advancement, satisfying ever stringent system needs and market trends. The Mitsubishi Electric IGBT Power Modules have been designed to exacting standards for the key ratings and characteristics required to provide optimum performance for switching operation. The application of the latest generation IGBT power modules to the UPS product line up and the latest control circuitry enables Mitsubishi Electric to keep pace with ever advancing technology change.

Mitsubishi Electric is the worlds top manufacturer of IGBT power devices (* See Note). Mitsubishi Electric not only understand and have a total in depth knowledge of the IGBT power device, but also know how best to apply and control the device within electronic equipment. This total integration enables Mitsubishi Electric to continuously provide UPS products that will combine optimum performance, quality and reliability, and continually satisfy the ever expanding stringent market demands.

* **Note:** In addition to the Mitsubishi Electric brand name, Mitsubishi Electric is also a majority shareholder of Powerex, Inc., a major manufacturer of power semiconductor devices.