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Semiconductors

Fuji Electric

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REVIEW

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CONTENTS

Cover photo:

In order to increase the efficiency of electric power usage, enhanced performance and an expanded range of applications is being pursued for the power semiconductors used in power electronics devices, not just in industrial fields, but in various other fields as well, such as automobile, new energy and information fields.

Fuji Electric is contributing to energy conservation efforts through commercializing power semiconductors that can be used with the latest power electronics technology.

The cover photo shows an IGBT (Insulated Gate Bipolar Transistor) module, having a structure that is suited to parallel connections and that aims to expand the range of applications to the new energy field, and an IGBT-PMC (Intelligent Power Module) for use in automobile drive systems, both of which employing high performance 6th ganaration “V-series” IGBT chips. With the widespread use of these modules throughout society, Fuji Electric hopes to make a significant contribution to the protection of the global environment.

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Fuji Electric's Semiconductors: Current Status and Future Outlook

Toru Hosen † **Kuniaki Yanagisawa** †

ABSTRACT

With the growth of new energy sectors, such as wind power and mega solar, large-capacity modules are being developed and commer-cialized and Fuji Electric's line-up of IGBT (insulated gate bipolar transistor) modules is rated up to 1,700 V/3,600 A. Wide bandgap semicon-ductors are being developed jointly with third-parties. High-speed discrete IGBTs for fast switching have been developed and are contributing to the realization of higher efficiency equipment. Power supply control ICs utilize a proprietary control method more energy efficient, smaller size and lower noise, and are contributing to the realization of higher performance equipment. Automotive devices such as IPS (intelligent power switch) and pressure sensors are being commercialized.

1. Introduction

Following the global recession of 2008, as a result of economic stimulus measures such as subsidies centering on the environmental sector as enacted by each country, the economic environment showed a sudden recovery in 2010. Recently, business relating to new types of energy, i.e., energy saving devices, environmentally-friendly vehicles, solar and wind power generation and the like, has expanded rapidly. Moreover, in Japan, record-setting heat waves continue, localized heavy rains are causing damage, and the phenomenon of extreme weather is being felt directly and concern about the environment is increasing more and more.

Since 2009, Fuji Electric has concentrated on a new 3-year plan for its "energy and environment business," and has announced its aim to contribute to society through this business. Power electronics technology is central to efforts to protect the global environment such as CO_2 reduction and to expand the field of renewable energy, and Fuji Electric has been working to innovate power electronics technology for many years. Power electronics technology is a key technology for converting energy into motive power, and power semiconductors, which are essential components, are becoming more and more important.

This paper focuses on the power semiconductors that Fuji Electric is working on and that will contribute to the energy and environmental field, and discusses the present status and future outlook for such representative power semiconductors as power modules, next-generation devices, power discretes, power supply ICs and devices for use in automobiles.

† Fuji Electric Co., Ltd.

2. Power Modules

In the field of power modules, the development of IGBT (insulated gate bipolar transistor) power modules has been advanced based upon the keywords of "energy" and "environment." Many product series have been introduced for applications in the conventional field of medium-capacity power generation, but with the expansion of the field of large-scale new energy power generation, including wind and mega-solar power generation and the like, the development and commercialization of large-capacity modules is being advanced. A 1,700 V series of IGBT modules with current ratings of up to 3,600 A has been produced, and samples of 3,300 V IGBT modules are being deployed.

The IGBT chips presently being used to configure IGBT power modules are mainly the "V Series" of 6th generation IGBT chips. The V Series uses microfabrication technology and the optimzed FS (field stop) structure, and features an improved trade-off between low on-voltage, high-speed switching and resistance to breakdown in order to achieve performance close to the theoretical limit. Fuji Electric is expanding its lineup of new power modules using this V Series chip and a new package structure. In particular, Fuji Electric's new PIM (power integrated module) and 6-in-1 module both use a PCB (printed circuit board) insertion method for connecting external terminals that enables the elimination of the soldering process. Additionally, with the new-structure 2-in-1 and 1-in-1 IGBT modules, the stray inductance inside the package has been reduced by 50%, and high reliability has been achieved. Furthermore, lead-free (RoHS*[1] compliant) materials are used, and high-temperature operation is possible up to 175 °C.

In addition, Fuji Electric has its proprietary technology to develop a RB-IGBT (reverse blocking IGBT)

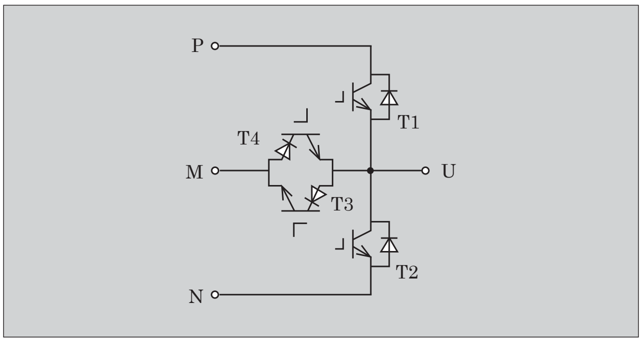

Fig.1 A-NPC inverter equivalent circuit

chip having reverse blocking capability for use in matrix converters and advanced NPC (A-NPC: advanced neutral-point-clamped) type inverters*2 that can be used to realize higher efficiency in equipment. Using this chip, an IGBT module for use in an A-NPC circuit in combination with a conventional IGBT as shown in Fig. 1, and a bidirectional switching IGBT module for use in a matrix converter have been developed.

Fuji Electric has developed IGBT modules and IPMs (intelligent power modules) for applying to hybrid vehicles, a plated IGBT having twice the current density of a general-purpose IGBT using a double-sided cooling package structure, a diode chip, and the like. All of these devices are either 600 V or 1,200 V products. In recent years, the motor capacities of hybrid and electric vehicles have increased, and with the increase in motor output current, higher efficiency through optimizing the module voltage has increasingly been demanded. In response to this demand, Fuji Electric has developed a 750 V IGBT module for mild hybrid vehicles that realizes an approximate 30% reduction in loss compared to previous modules.

In the field of power modules, technical development to improve further the performance of IGBTs as key devices in the "energy and environment" field, and product development to meet customer needs are being carried out.

3. Next-generation Devices

As 6th generation IGBTs, which are the mainstream devices of today, are approaching the theoretical performance limit of silicon, dramatic performance improvements as in the past are no longer expected. Therefore, attention has shifted to next-generation devices that use silicon carbide (SiC) and gallium nitride (GaN) materials. Since 2009, Fuji Electric has actively been developing these next-generation devices jointly with outside organizations, and is endeavoring to accelerate development aiming for practical application.

*1: RoHS directive: EU (European Union) directive on the restriction of the use of certain hazardous substances in electrical and electronic equipment.

*2: 3-level inverter technology: See explanation on page 108

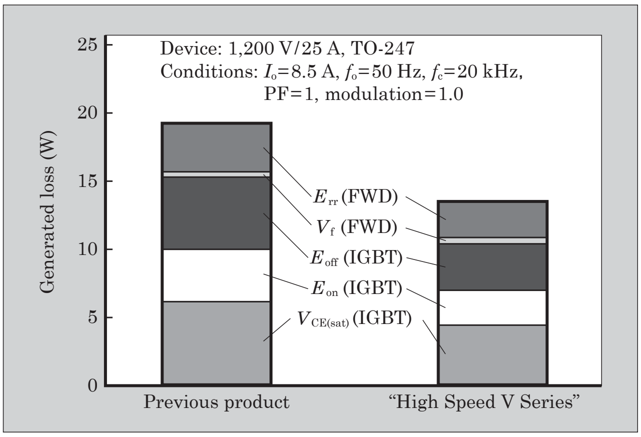

Fig.2 Loss breakdowns in 1,200 V series discrete IGBTs

Using SiC material, in joint development with the National Institute of Advanced Science and Technology, Fuji Electric is advancing the development of MOSFETs (metal oxide semiconductor field effect transistors) and schottky barrier diodes. Through using SiC devices, loss can be reduced by 50% or more compared to conventional silicon, and SiC technology is considered to hold promise for making significant contributions to technical innovation in power electronic devices.

Meanwhile, for GaN device development, Fuji Electric and the Furukawa Electric Co. have jointly established the Technical Research Association for Next-Generation Power Devices, and are advancing research toward practical applications. GaN can be formed on a silicon wafer, and is therefore potentially less expensive than SiC.

4. Power Discretes

As a result of the increasing popularity of the Internet in recent years, and for such purposes as storing digital photographs or other digital data, there has been an increase in small computer applied systems and the importance of small UPS (uninterruptible power supplies) has been recognized. Additionally, as solar power has become more popular, power conditioners have also been used increasingly. Because these UPSs and power conditioners are running at all times, higher efficiency to conserve resources and reduce operating costs is strongly demanded. To meet these demands, Fuji Electric has applied 6th generation IGBT technology to develop a "High Speed V Series" of high-speed discrete IGBTs that are capable of high-speed switching. An internal FWD (free wheeling diode) also aims for higher speed, and in the 1,200 V product, achieves an approximate 30% reduction in loss compared to the conventional product as shown in Fig. 2.

Fuji Electric is also developing various devices for use in switching power supplies in flat-screen TVs, PCs, servers and the like. For high-voltage MOSFETs, Fuji Electric has developed and deployed the "SuperFAP-E³ Series" of planar MOSFETs featuring the world's best $R_{on}×A$ (normalized on-state resistance per unit area) performance. The SuperFAP-E³ Series achieves low loss and low noise, and has contributed to the higher efficiency of equipment. In addition, Fuji Electric is also moving ahead with the development of a Super Junction MOSFET (SJ-MOSFET) having the world's best $R_{on}×A$ performance of approximately one-quarter that of the "SuperFAP-E³ Series." The SJ-MOSFET, with its low on-state resistance, enables loss to be reduced by approximately 15% when used in the power factor correction circuit of a power supply. Development continues to accelerate toward early commercialization.

Meanwhile, super low I_R Schottky barrier diodes and large capacity diodes of greater than 30 A are being developed into product lines, and are being deployed in solar power and large capacity power supply applications.

To comply with increasingly severe demands for higher efficiency, smaller size and so on, Fuji Electric seeks not only innovation with conventional silicon technology, but is also accelerating the development of next-generation devices made from materials such as SiC and GaN and that realize dramatically lower loss compared to silicon.

5. Power Supply LCs

For power supply ICs, Fuji Electric has developed a proprietary control method that, when applied to products, realizes low energy consumption, small-size and lower noise in switching power supplies, and contributes to the higher performance of devices. Switching power supplies are commonly used to reduce the energy consumption of devices, but because a capacitor-input type rectification and smoothing method is employed, there arises a problem of higher harmonics on the power line, which is subject to regulatory oversight. To solve this problem, a power factor correction (PFC) circuit is often used. Meanwhile, energy-saving regulations for electronic devices are becoming stricter year-by-year and lower standby power consumption and higher efficiency during light-load operation are sought, and compliance in the PFC circuit is also important. Responding to these requests, Fuji Electric has developed the "FA5590 Series" of 2nd generation critical-mode PFC control ICs that realize higher efficiency as shown in Fig. 3 by limiting the maximum oscillation frequency of switching during light-load operation and that enable a reduction in peripheral circuit components.

Additionally, Fuji Electric has also developed technology for a high voltage IC (HVIC) that contains a built-in high-side driver for relatively high-capacity power supplies such as for servers. The HVIC technology developed by Fuji Electric has a breakdown voltage of 800 V, and because this is a higher breakdown voltage than that of the driving MOSFET, there is little risk of damage. Furthermore, the turn-on and turn-off propagation delay time has been set to less than 100 ns, which contributes to higher efficiency. In the future, this newly developed technology will be applied to make commercial products.

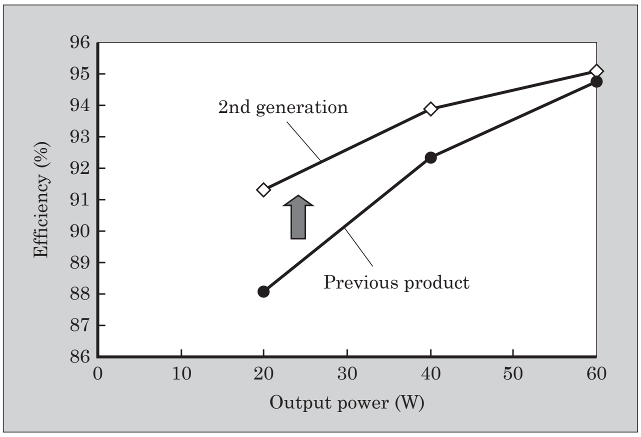

Fig.3 Efficiency of power supply control ICs

Fuji Electric is also endeavoring to advance simulation technology that will support product development. To improve design efficiency, ample verification through simulation is essential, and this special issue of the Fuji Electric Review introduces one aspect of the simulation technology.

To support requests for higher efficiency, lower energy consumption, smaller size and so on for power supply control ICs, Fuji Electric will continue to research and develop proprietary control technology and distinctive process technology.

6. Semiconductor Devices for Automobiles

Based on competitive and advanced device technology developed for industrial and power supply applications, Fuji Electric has applied high reliability technology to deploy IPSs (intelligent power switches), pressure sensors, IGBTs for ignitors, IGBT drive ICs for hybrid vehicles, and so on for the automotive field. With "environmental friendliness," "safety" and "comfort" as key words, products capable of realizing these concepts are desired. An intelligent power switch (IPS) for linear control and a 6th generation small pressure sensor that support such requests are introduced below.

(1) IPS "F5064H" for linear control

For automatic transmissions, linear control systems capable of varying the oil pressure linearly have been increasing in usage, and the detection of current flowing through a linear solenoid coil must be performed with high accuracy. For this purpose, a new circuit, device optimization and the like is carried out for the recently developed IPS, and the device is

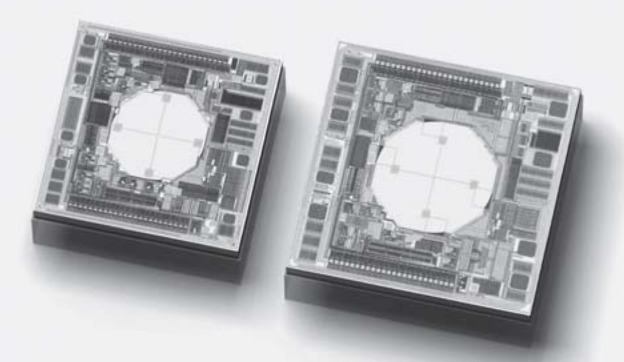

Fig.4 Pressure sensor chips

equipped with an op-amp for high accuracy detection.

Additionally, to protect the input stage of the op-amp, the device is provided internally with a protection element having ESD (electrostatic discharge) tolerance of 30 kV or higher, and also a function that turns off the output when the input terminal is in an open state. By using QPJ (quasi plane junction) technology, commonly used in high voltage MOSFETs, in the output stage MOSFET, 25% lower $R_{on} \times A$ than previous device was realized. Because of the high accuracy detection and low loss, this device can contribute to miniaturization of the ECU (engine control unit).

(2) 6th generation small pressure sensors

In the automotive field, as well, environmentally friendly initiatives such as fuel-efficient cars are also being advanced. Pressure sensors are key devices for making engines more efficient (higher fuel efficiency) and cleaner, and are used to measure the intake air pressure, atmospheric pressure and so on. Fuji Electric is mass-producing a 5th generation pressure sensor based on a CMOS (complementary metal-oxide semiconductor) process and incorporating high reliability circuit technology and advanced MEMS (microelectromechanical system) technology, and that is applied to automobiles and motorcycles both in Japan and overseas.

The newly developed 6th generation pressure sensor has an optimized sensing part shape (diaphragm) and a miniaturized circuit to maintain the functions and performance of the 5th generation while reducing the chip size to 70%. Fig. 4 shows a comparison of the external appearances. Fuji Electric plans to apply this technology to expand its product lineup in the future.

In addition to the products introduced herein, Fuji Electric's other automotive devices include a single-chip ignitor that uses Fuji Electric's proprietary technology. By levering its proprietary technology in the future and also incorporating new technologies, Fuji Electric will continue to develop high reliability and high performance products to satisfy customer needs.

7. Postscript

Based on the key words of "energy" and "environment," Fuji Electric has established the goal of contributing to society as a business objective. Power electronics technology will form the basis for achieving this goal, and technical innovation in power semiconductors, which are critical components, will also be needed.

As described in this paper, Fuji Electric is endeavoring to develop distinctive power semiconductor products that will contribute to the energy and environmental field, and will realize lower loss, higher functionality, smaller size, lower noise and higher reliability with innovative proprietary technology. Hereinafter, so as to be able to respond quickly to customer demands, Fuji Electric will continuously develop technology and will develop products from the customer's perspective.

IGBT Module for Advanced NPC Topology

Kosuke Komatsu † **Takahito Harada** † **Haruo Nakazawa** †

ABSTRACT

A new IGBT module has been developed to realize advanced NPC (A-NPC: advanced neutral-point-clamped) inverters. The IGBT (insulated gate bipolar transistor) module used for A-NPC minimized power loss by using a 6th generation IGBT and FWD (free wheeling diode), as well as a 2nd generation RB-IGBT (reverse blocking IGBT). The internal inductance between each of the main terminals is less than 40 nH, and the terminal layout was optimized to reduce the A-NPC inverter size. This product can be applied to reduce the number of devices inside equipment, and can also contribute to the development of various types of power conversion equipment having lower power loss and higher power conversion efficiency.

1. Introduction

In recent years, the reduction of CO_2 emissions has become one of the most important challenges facing for humanity. Accordingly, various efforts to reduce such emissions are being advanced on a global scale.

To contribute to a solution, in power electronics, energy savings has been promoted and inverter/converter systems, which are an effective means for achieving energy savings, have been developed and their use promoted. These systems are used not only in consumption-type applications such as motors, traction and FA (factory automation) systems, but have spread to power generation, transmission and power supply applications such as UPSs, wind power generators, solar power generators and fuel cell generators.

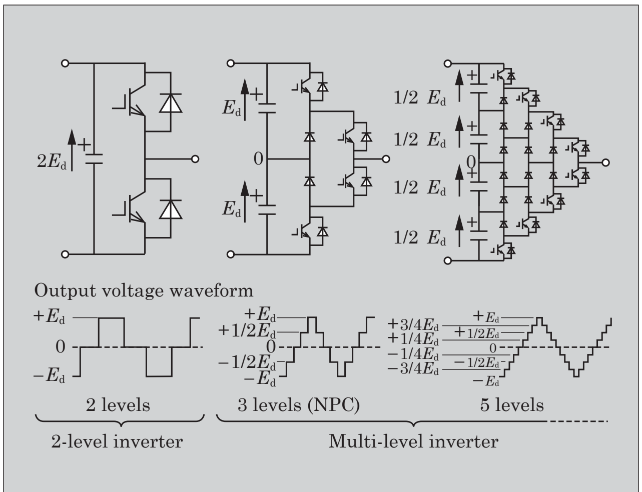

Fig.1 Circuit system and output voltage waveform for each inverter

In these applications, improved power conversion efficiency of the power conversion system is sought, and numbers of studies are being carried out. Several NPC (neutral-point-clamped) inverters have been proposed for the multilevel inverter, which one of the most effective ways to increase power conversion efficiency[(1)]. In recent years, NPC inverters, having neutral-point clamps implemented with diodes, have begun to be used in inverters for AC driving, UPSs and the like. Fig. 1 shows circuit diagrams of a conventional 2-level inverter and a multi-level inverter*[1]. As can be seen from the output voltage waveforms of Fig. 1, the output voltage waveform of the multi-level inverter is closer to an ideal sine wave. Thus, the NPC inverter can be used effectively to reduce switching loss and to miniaturize filters[(2)].

The NPC inverter, however, uses many semiconductor devices and has a complicated configuration. In terms of conduction loss and cost, application to system of less than several hundred kVA is particularly challenging.

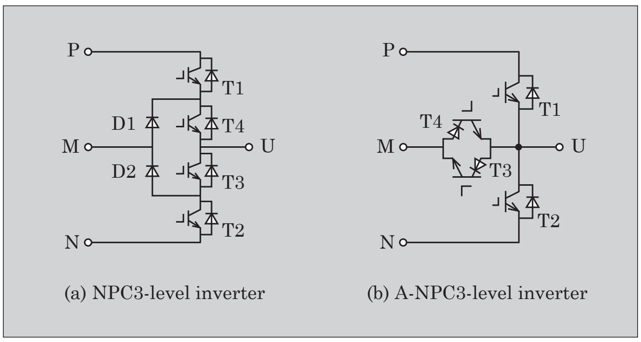

Fig.2 Equivalent circuits

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*1: 3-level inverter technology: See explanation on page 108 for further details

To solve this problem, Fuji Electric uses one of its proprietary power semiconductors, an RB-IGBT (reverse-blocking IGBT(3)), for the neutral point clamp and has developed an IGBT insulated gate bipolar transistor) module for an advanced NPC (A-NPC) used as bidirectional switch(4). An equivalent circuit is shown in Fig. 2.

Fuji Electric has developed a UPS that fully utilizes the characteristics of this A-NPC, and through releasing this UPS on the market, has contributed positively to the "energy" and "environment" fields.

An overview and a description of the technical development of the IGBT module for A-NPC topology are presented herein.

2. Characteristics of IGBT Module for A-NPC Topology

2.1 Ratings and external appearance

Table 1 lists the ratings, package and the like, and Fig. 3 shows the external appearance of the IGBT module for A-NPC topology.

The IGBT module for A-NPC topology is housed in a 4-in-1 package, and is configured from 1,200 V/300 A IGBT devices T1 and T2, which are the main switches, and 600 V/300 A RB-IGBT devices T3 and T4, which are bidirectional switches, (see Fig. 2(b)).

T1 and T2 have the same circuit configuration as standard 2-in-1 modules. The bidirectional switches T3 and T4 are configured from RB-IGBTs in an anti-parallel connection.

2.2 Device electrical characteristics

(1) Main switches

A 1,200 V-rated 6th generation "V Series" IGBT and a FWD (free wheeling diode) are used in the main switches of T1 and T2.

For the 6th generation V Series, the surface structure was optimized and the wafer was made thinner to achieve lower resistance of the drift layer and to reduce the on-state voltage $V_{CE(sat)}$ and switching loss. In addition, controllability of the turn-on di/dt was improved so as to realize lower radiation noise than with a conventional device.

(2) Bidirectional switches

A 600 V-rated 2nd generation RB-IGBT was used in the bidirectional switches of T3 and T4.

An RB-IGBT is a semiconductor device having reverse blocking capability of which a conventional IGBT is incapable. Previously, bidirectional switches had to be configured with an IGBT and a diode. But, by using an RB-IGBT, there is no need for a diode to maintain the reverse blocking capability, and on-state voltage can be reduced.

Fig. 4 compares the on-state voltage of a conventional NPC inverter and an A-NPC inverter.

In a conventional NPC inverter, the on-state voltage was large for all current routes (modes 1 to 4), because either two IGBTs or diodes are connected in series, or an IGBT and a diode are connected in series in the circuit. On the other hand, in an A-NPC inverter, because devices having twice the rated voltage of the NPC inverter are used and because RB-IGBTs

Fig.3 External appearance of IGBT module for A-NPC topology

I_c=300 A, V_{GE}=+15 V, T_j=25°C

	Mode 1	Mode 2	Mode 3	Mode 4
NPC inverter	3.20 V	3.20 V	3.20 V	3.20 V
A-NPC inverter	1.85 V	1.70 V	2.45 V	2.45 V

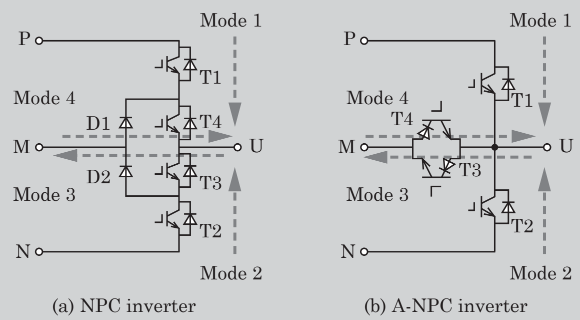

Fig.4 Comparison of on-state voltages for NPC inverter and A-NPC inverter

Table 1 Summary of IGBT module for A-NPC topology

Model name	Package dimensions	Rated voltage	Rated current
4 MBI300VG-120R-50	L110×W80×H30 (mm)	1,200 V (main switch part)	300 A (main switch part)
		600 V (bidirectional switch part)	300 A (bidirectional switch part)

are used in T3 and T4, the number of devices through which current flows is halved for all modes 1 to 4.

As a result, compared to a module for a conventional NPC 3-level inverter, the module for an A-NPC 3-level inverter realizes approximately 30% less conduction loss, keeping equivalent switching loss and noise.

An RB-IGBT has the same fundamental structure as a conventional IGBT. Therefore, the tradeoff between switching loss and on-state voltage in a RB-IGBT does not differ from that of a conventional IGBT. When reverse biased, the recovery characteristics are the same as for a conventional FWD. Fig. 5 shows the curve of the tradeoff between on-state voltage and turn-off loss in an RB-IGBT. The curve has the same slope as an IGBT+FWD combination, but the $V_{CE(sat)}$ is smaller because of the fewer conducting devices.

2.3 Package for A-NPC inverters

For this product, optimization design with an emphasis on the following items was carried out to realize an optimal package for configuring an A-NPC inverter.

(a) Main pins P, U, N, and M shall be arranged to facilitate the placement of a snubber capacitor for reducing surge voltage

(b) The U output pin shall be placed as far as possible from the control pin, and the output current shall not affect the control signals

(c) The package size shall be selected based on the external shape and dimensions of conventional products, and shall be made as small as possible

As a result, the pin layout conditions were satisfied and a package size of 110×80 (mm), equivalent to that of the M247, was achieved.

2.4 Low inductance package

The circuit inductance directly affects the surge voltage generated at turn-off of the semiconductor device. If a conventional 2-in-1 module and a 1-in-1 module were used to realize the same circuit configuration as this product, the total inductance of the bus bar for connecting the modules and the internal inductance of the package would be a large value of more than 100 nH, and the A-NPC inverter would be difficult to realize. Therefore, this product houses the 2-in-1 topology and the 1-in-1 topology inside a single package so as to reduce the bus bar inductance significantly. In each current route, the internal inductance has become the equivalent package internal inductance of a conventional 2-in-1 module (internal inductance of 40 nH or less in each P-N, P-M and M-N current route) to a level at which the surge voltage at turn-off can be suppressed.

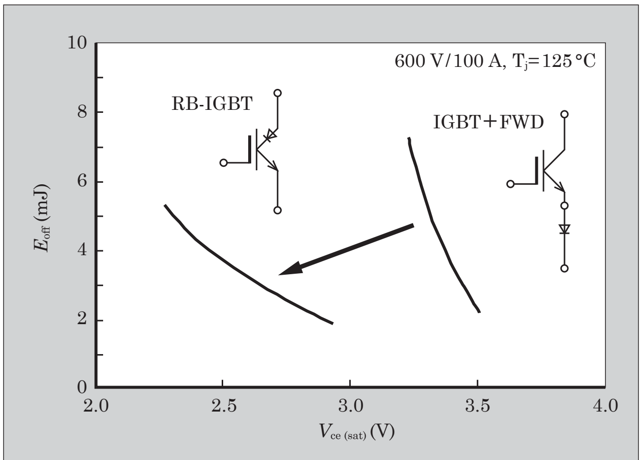

Fig.5 Curve of RB-IGBT tradeoff between on-state voltage and turn-off loss

2.5 High reliability package

In this product, the DCB (direct copper bonding) substrate for mounting the semiconductor devices is subdivided into four substrates, and as a result, compared to a conventional product of the same size (M236 single substrate), less amount of stress is generated on the substrate and the solder underneath the substrate at the time of thermal contraction.

Fig. 6 shows a comparison, based on FEM (finite element method) analysis, of the strain on the solder underneath the DCB substrate that is generated during thermal cycle tests. At high temperatures, if the ratio of solder strain generated with a single substrate is 1.0, the ratio of strain with 4 substrates is 0.45, which is a 55% reduction in the strain.

Accordingly, compared to a conventional product, improved tolerance to thermal cycle testing and reliability against thermal expansion and thermal contraction can be expected.

Furthermore, as an environmental measure, the package is lead-free and is in compliance with the European RoHS Directive*2.

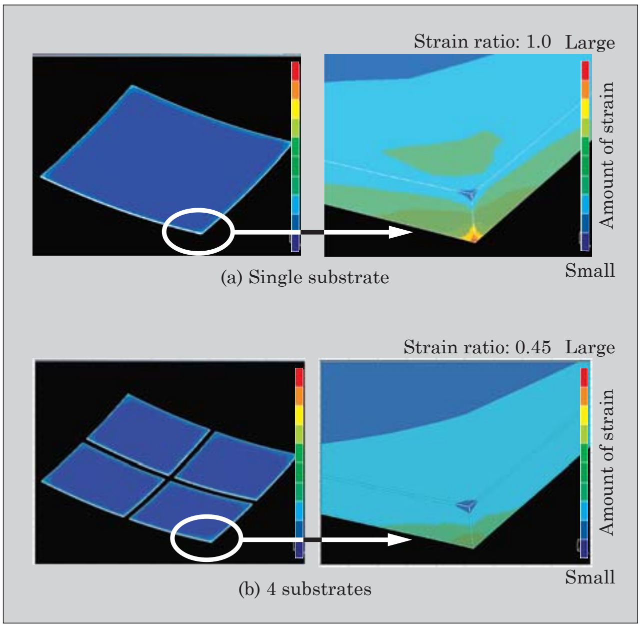

Fig.6 FEM analysis results (at high temperature)

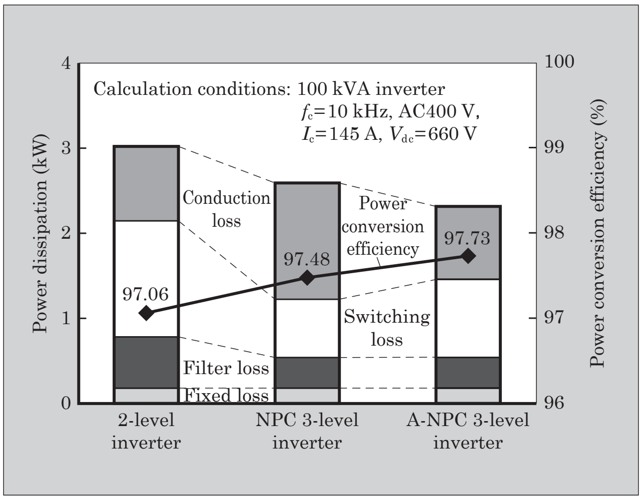

Fig.7 Comparison of power dissipation and power conversion efficiency for each inverter

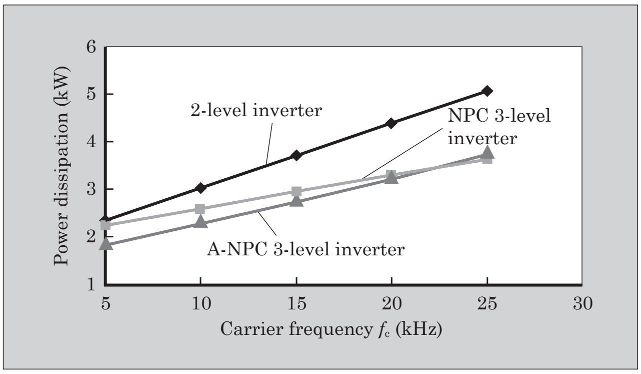

Fig.8 Carrier frequency dependency of power dissipation

3. Power Dissipation / Power Conversion Efficiency

Fig. 7 compares the power dissipation and power conversion efficiency of the conventional 2-level inverter, the NPC 3-level inverter and the A-NPC 3-level inverter when operated under the same conditions.

For the conventional 2-level inverter, the characteristics of a 1,200 V 6th generation V Series device were used, and for the NPC inverter, the characteristics of a 600 V 6th generation V Series device were used. The internal inductance of the module for NPC inverter was assumed to be the same as that of the module for A-NPC inverters.

The inverter operating conditions were f_c=10 kHz, DC voltage=660 V and output current=145 A. As a result, the A-NPC inverter exhibited the smallest power dissipation and was 23% lower than the conventional 2-level inverter and 9% lower than the NPC inverter. Additionally, A-NPC has the highest power conversion efficiency of 97.73%, which was an improvement of 0.25 percentage points over the NPC inverter and 0.67 percentage points over the conventional 2-level inverter.

The reasons for these results are as follows.

(a) Reduced filter loss: Less higher harmonics in output voltage waveform due to use of 3 levels
(b) Reduced switching loss due to use of 3 levels
(c) Reduced conduction loss: Combination of devices having different voltage ratings and use of RB-IGBT

In addition, Fig. 8 compares the carrier frequency dependency of power dissipation. Basically, power dissipation is lower with a 3-level inverter than with a 2-level inverter. However, in comparing the NPC inverter and A-NPC inverter, a cross-point can be seen at f_c=21.5 kHz. This suggests that with the A-NPC inverter, switching loss accounts for a larger percentage of the power dissipation. Additionally, this shows that the A-NPC inverter is effective for applications where f_c is 21.5 kHz or less.

*2: RoHS directive: EU (European Union) directive on the restriction of the use of certain hazardous substances in electrical and electronic equipment

4. Postscript

An overview and description of the characteristics of a new IGBT module for use in A-NPC inverter circuits have been presented. With this product, lower noise by 3-level control, reduced switching loss by using a 6th generation IGBT and FWD, reduced conduction loss by using a 2nd generation RB-IGBT, optimization of the pin layout, lower surge voltage by reducing the package internal inductance and so on, have been realized. As a result, our customers are able to design A-NPC inverters with greater ease. In addition, the reduced number of devices used, and the miniaturization and common usage of constituent components, enable our customers to realize lower cost equipment.

For applications involving a relatively low carrier frequency, in terms of the power dissipation and power conversion efficiency, higher performance can be achieved with the A-NPC inverter than with either a 2-level inverter or an NPC inverter.

Fuji Electric, in addition to improving device performance, is also advancing a package design capable of offering further miniaturization and higher reliability, and intends to continue to develop modules in response to market demands.

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Neutral-Point-Clamped 3-Level Power Converters" Proc. of IPEC '10, 2010, p.523-527.

High Power IGBT Module for Three-level Inverter

Takashi Nishimura [†] **Takatoshi Kobayashi** [†] **Yoshitaka Nishimura** [†]

ABSTRACT

In recent years, power conversion equipment used in the field of new energy and the field of traction advance high efficiency by a multi-level inverter system. Fuji Electric has developed a new high-power IGBT (insulated gate bipolar transistor) module having high isolation voltages which could apply to three-level inverter as one of multi-level inverter systems. Newly developed high-power IGBT modules have rating of 600 to 3,600 A/1,700 V. They have three packages and product lineup for 1-in-1 and 2-in-1 modules.

1. Introduction

With advances in high voltage and high power device technology, the application range of IGBT (Insulated Gate Bipolar Transistor) modules has expanded to industrial-use high-voltage high-power inverters.

In recent years, emerging countries have been experiencing rapid economic growth, but their development of an electricity infrastructure is still lagging, and severe power shortages have occurred for years. Also, because of delays in the development of a transportation infrastructure, the use of automobiles and the like that run on fossil fuels has increased, the emission of greenhouse gases (such as CO_2) have risen year after year, and there is a concern that these trends will accelerate global warming.

Wind-power and solar-power are promising clean energy sources that do not emit greenhouse gases at the time of power generation, and facilities for the generation of wind and solar power are being installed throughout the world. In addition, high-speed railways that link major cities and the electric railways and streetcars that connect to the suburbs are capable of transporting large amounts of people and cargo. Furthermore, these energy sources are attracting attention because they do not emit greenhouse gases, and their development is progressing.

Fuji Electric has developed and deployed a high

Table 1 Product lineup

	Product type	Package type	Package size (mm)	Rated voltage (V)	Rated current (A)	Base material	Isolation substrate	Isolation voltage V_{iso} (kV)
1 in 1	1MBI1200U4C-170	M151	130×140×38	1,700	1,200	Cu	Silicon nitride (Si_3N_4)	4.0
	1MBI1600U4C-170				1,600			
	1MBI2400U4D-170	M152	190×140×38		2,400			
	1MBI3600U4D-170				3,600			
	1MBI1200U4C-170	M151	130×140×38	1,700	1,200	Aluminum silicon carbide (AlSiC)	Aluminum nitride (AlN)	6.0
	1MBI1600U4C-170				1,600			
	1MBI2400U4D-170	M152	190×140×38		2,400			
	1MBI3600U4D-170				3,600			
2 in 1	2MBI600U4 G-170	M256	130×140×38	1,700	600	Cu	Silicon nitride (Si_3N_4)	4.0
	2MBI800U4 G-170				800			
	2MBI1200U4 G-170				1,200			
	2MBI600U4 G-170	M256	130×140×38	1,700	600	Aluminum silicon carbide (AlSiC)	Aluminum nitride (AlN)	6.0
	2MBI800U4 G-170				800			
	2MBI1200U4 G-170				1,200			

(shaded) : New product

† Fuji Electric Co., Ltd.

power IGBT module for use in the fields of high-power industrial applications and clean energy.

In recent power conversion systems for wind-power, solar-power and traction use, the use of a multi-level inverter system to increase the efficiency (reduce the conversion loss) of the equipment is considered.

A high-power 1,700 V IGBT module having a high isolation capability and targeting application to 3-level inverters (see explanation on page 108), a type of multi-level inverter system, and having a power cycle tolerance that also accommodates application to the traction field has been newly developed. This paper presents an overview and description of the technical development of this high power IGBT module.

2. Product Lineup

The product lineup of newly developed high power IGBT modules is shown in Table 1. The product lineup consists of seven models having a rated voltage of 1,700 V and rated currents ranging from 1,200 to 3,600 A for the 1-in-1 module and 600 to 1,200 A for the 2-in-1 module.

Fig. 1 shows the appearance of the packages.

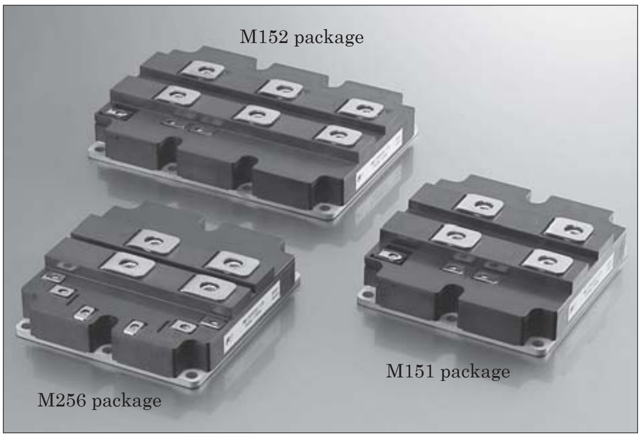

Fig.1 External appearance of high-power IGBT module package

Table 2 Absolute maximum ratings and characteristics (model: 1MBI1200U4C-170X)

(a) Maximum ratings ($T_j = T_c = 25$ °C, unless otherwise indicated)

Item	Symbol	Condition		Rating	Unit
Collector-emitter voltage	V_{CES}	$V_{GE} = 0$ V		1,700	V
Gate-emitter voltage	V_{GES}	–		±20	V
Collector current	$I_{c\ (DC)}$	Continuous	$T_c = 80$ °C	1,200	A
	$I_{c\ (Pulse)}$	1 ms	$T_c = 80$ °C	2,400	A
Collector power dissipation	P_c	–		6,250	W
Max. junction temperature	$T_{j\ max.}$	–		150	°C
Storage temperature	T_{stg}	–		−40〜+125	°C
Isolation voltage	V_{iso}	AC: 1 min		6,0	kV

(b) Electrical characteristics ($T_j = T_c = 25$ °C, unless otherwise indicated)

Item	Symbol	Condition		Minimum	Typical	Maximum	Unit
Collector-emitter leakage current	I_{CES}	$V_{GE} = 0$ V, $T_j = 125$ °C, $V_{CE} = 1{,}700$ V		–	–	1.0	mA
Gate-emitter leakage current	I_{GES}	$V_{GE} = \pm 20$ V		–	–	2.4	μA
Gate-emitter threshold voltage	$V_{GE\ (th)}$	$V_{CE} = 20$ V, $I_c = 1.2$ A		5.5	6.5	7.5	V
Saturation voltage (chip)	$V_{CE\ (sat)}$	$V_{GE} = +15$ V, $I_c = 1{,}200$ A	$T_j = 25$ °C	–	2.25	2.40	V
			$T_j = 125$ °C	–	2.65	–	
Input capacitance	C_{ies}	$V_{GE} = 0$ V, $V_{CE} = 10$ V, $f = 1$ MHz		–	112	–	nF
Turn-on time	t_{on}	$V_{cc} = 900$ V, $I_c = 1{,}200$ A, $V_{GE} = \pm 15$ V, $T_j = 125$ °C		–	1.80	–	μs
	t_r			–	0.85	–	
Turn-off time	t_{off}			–	1.30	–	
	t_f			–	0.35	–	
Forward on voltage (chip)	V_F	$V_{GE} = 0$ V, $I_F = 1{,}200$ A	$T_j = 25$ °C	–	1.80	2.15	V
			$T_j = 125$ °C	–	2.00	–	
Reverse recovery time	t_{rr}	$V_{cc} = 900$ V, $I_F = 1{,}200$ A, $T_j = 125$ °C		–	0.35	–	μs

(c) Thermal characteristics

Item	Symbol	Condition	Minimum	Typical	Maximum	Unit
Thermal resistance	$R_{th\ (j\text{-}c)}$	IGBT	–	–	0.020	K/W
		FWD	–	–	0.033	

3. Electrical Characteristics

The electrical characteristics are described below for the 1-in-1 1,200 A/1,700 V module, as an example. The maximum ratings and characteristics are listed in Table 2.

3.1 V-I characteristics

Fig. 2 shows the output characteristics and Fig. 3 shows the forward V–I characteristics of the module.

In the IGBT and FWD (free wheeling diode) chips, the saturation voltage and forward voltage both have a positive temperature coefficient. When the junction temperature increases in a chip having a positive temperature coefficient, the chip operates to equalize the junction temperature among chips connected in parallel, and auto-regulates current imbalances. These chips are well suited for a high power IGBT module employing many parallel chip connections.

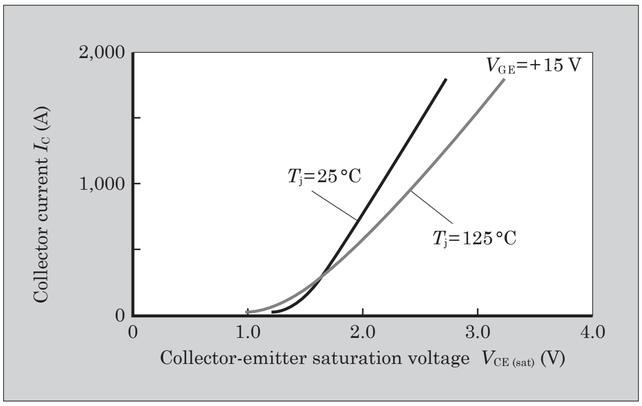

Fig.2 Saturation voltage – collector current characteristics

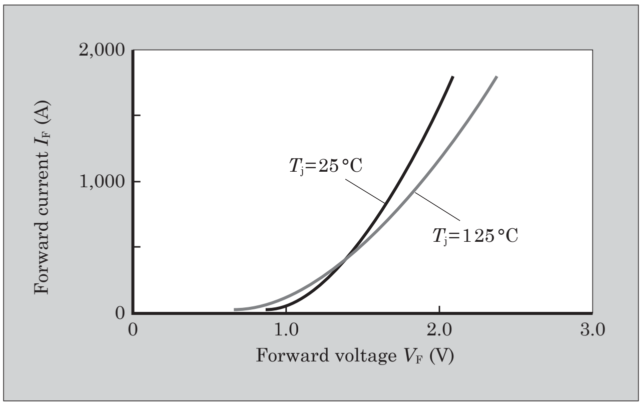

Fig.3 Forward V-I characteristics

3.2 Diode reverse recovery characteristics

High power IGBT modules are often used in applications where the stray inductance is large, and the possibility exists that the surge voltage generated at turn-off or during reverse recovery of the FWD may exceed the voltage tolerance of the module. The gate resistance can be increased to limit the surge voltage, however. On the other hand, as a result of the increase in the switching energy (turn-on and turn-off loss), there are expected to be some cases in which, depending upon the operating conditions of the equipment, a high power IGBT cannot be used.

An active clamping circuit inserted between the gate and collector is able to limit the surge voltage generated at turn-off without increasing the off-gate resistance of the gate drive circuit. The surge voltage generated during reverse recovery operation of the FWD, however, is determined by the turn-on d*i*/d*t* of

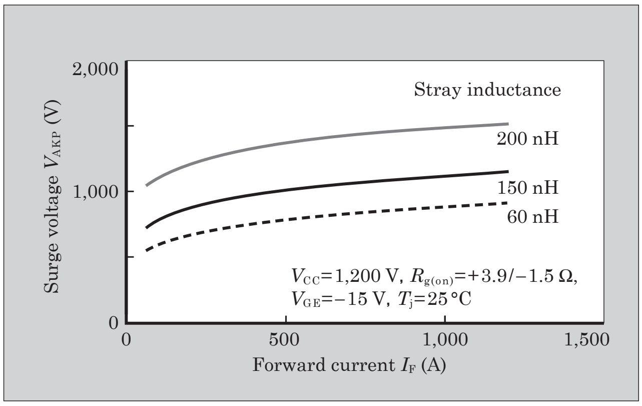

Fig.4 Reverse recovery surge voltage characteristics

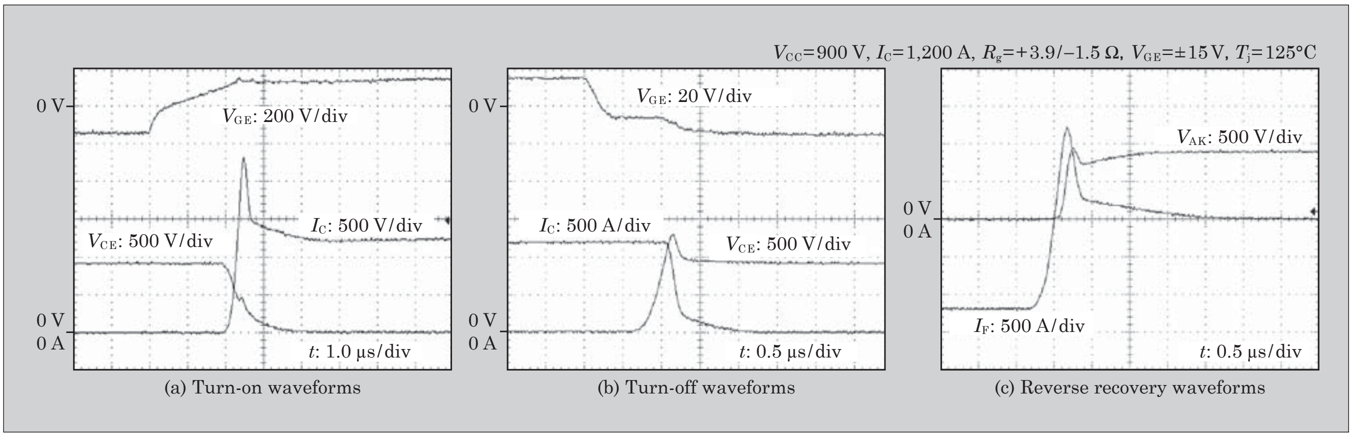

Fig.5 Switching waveform (inductive load)

the IGBT and the stray inductance, and therefore the on-gate resistance must be increased to limit this surge voltage.

The module is equipped with a U4 series IGBT designed with reduced turn-on di/dt to improve the controllability of the turn-on di/dt by gate resistance and requiring significantly lower turn-on energy, and a diode chip with an optimized design to reduce surge voltage during reverse recovery.

Fig. 4 shows the dependence of the surge voltage and stray inductance. It can be seen that the surge voltage is limited, even if the stray inductance is large.

3.3 Switching characteristics

Fig. 5 shows the turn-on, turn-off and reverse recovery waveforms (for an inductive load) of a module at the rated current of 1,200 A and under the conditions of V_{cc}=900 V, R_g=+3.9/−1.5 Ω, and T_j=125 °C. The switching energy is 350 mJ at turn-on, 390 mJ at turn-off and 380 mJ at reverse recovery. Fig. 6 shows the I_c and I_f dependence and Fig. 7 shows the R_g dependence of the switching energy.

4. Package Technologies

4.1 Increasing the isolation voltage V_{iso}

The energy-generating capacity of wind and solar power is highly dependent on the weather. To convey the generated energy to a transmission line requires the use of high-efficiency inverters. New designs for traction use power conversion equipment are also trending toward higher efficiency at an accelerating pace.

2-level inverters, which are generally used for a wide range of applications, have few components, are easy to control and are inexpensive, but have a slightly lower conversion efficiency than 3-level inverters. For this reason, 3-level inverter devices are increasingly being used in newly designed power conversion systems.

A module used in a 3-level inverter device is required to have an isolation voltage V_{iso} of at least 5.4 kV for a 1.7 kV module. However, the industrial-use high power IGBT modules presently being mass-produced are only able to achieve isolation voltages of up to 4.0 kV for a 1.7 kV module. To achieve isolation voltage of 5.4 kV or higher, the following technologies must be applied.

In order to achieve greater isolation, the materials of the isolation substrate must be changed and the isolation substrate thickness and the design of the creepage distance (distance from the edge of the isolating substrate to the front side Cu pattern) must be optimized, and so on. As shown in Fig. 8, there are two modes of isolation breakdown, penetration and creepage. The penetration mode can be avoided by increasing the thickness of the isolation substrate. However, there is a resulting trade-off in the thermal resistance of the module, and the thickness must be selected to minimize the increase in thermal resistance. Creepage mode breakdown is interfacial breakdown occurring at the boundary between the front side of the isolating substrate and the silicone gel. Optimization of the design of the creepage distance is the most important factor for preventing creepage mode breakdown.

Fig. 9 shows the simulation results of electric field intensity when the isolation substrate thickness and the substrate front side distance are constant. By optimizing the ratio between the front side distance L and the back side distance l, the intensity of the electric field generated at the front side Cu pattern at the boundary between the front side of the isolating substrate and the silicone gel is limited, indicating that the electric field intensity can be distributed to the back side Cu pattern.

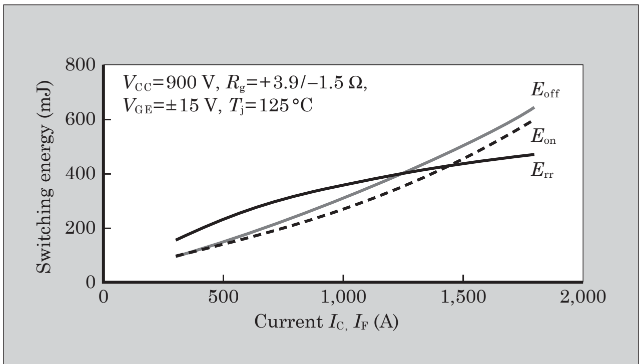

Fig.6 I_c, I_f dependency of switching energy

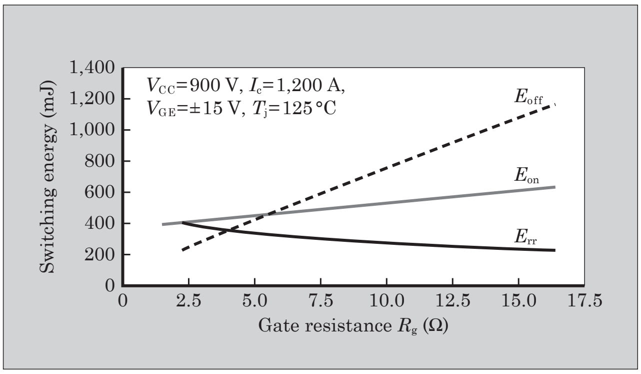

Fig.7 R_g dependency of switching energy

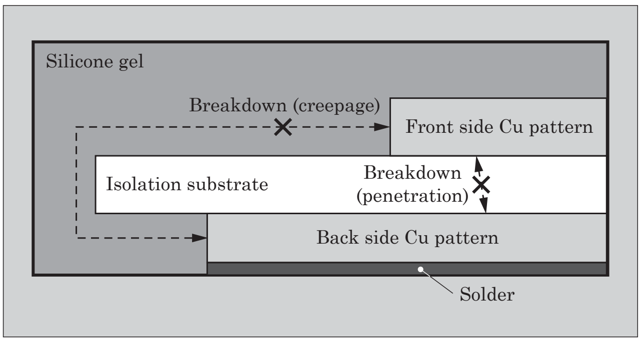

Fig.8 Cross-sectional view of isolation substrate

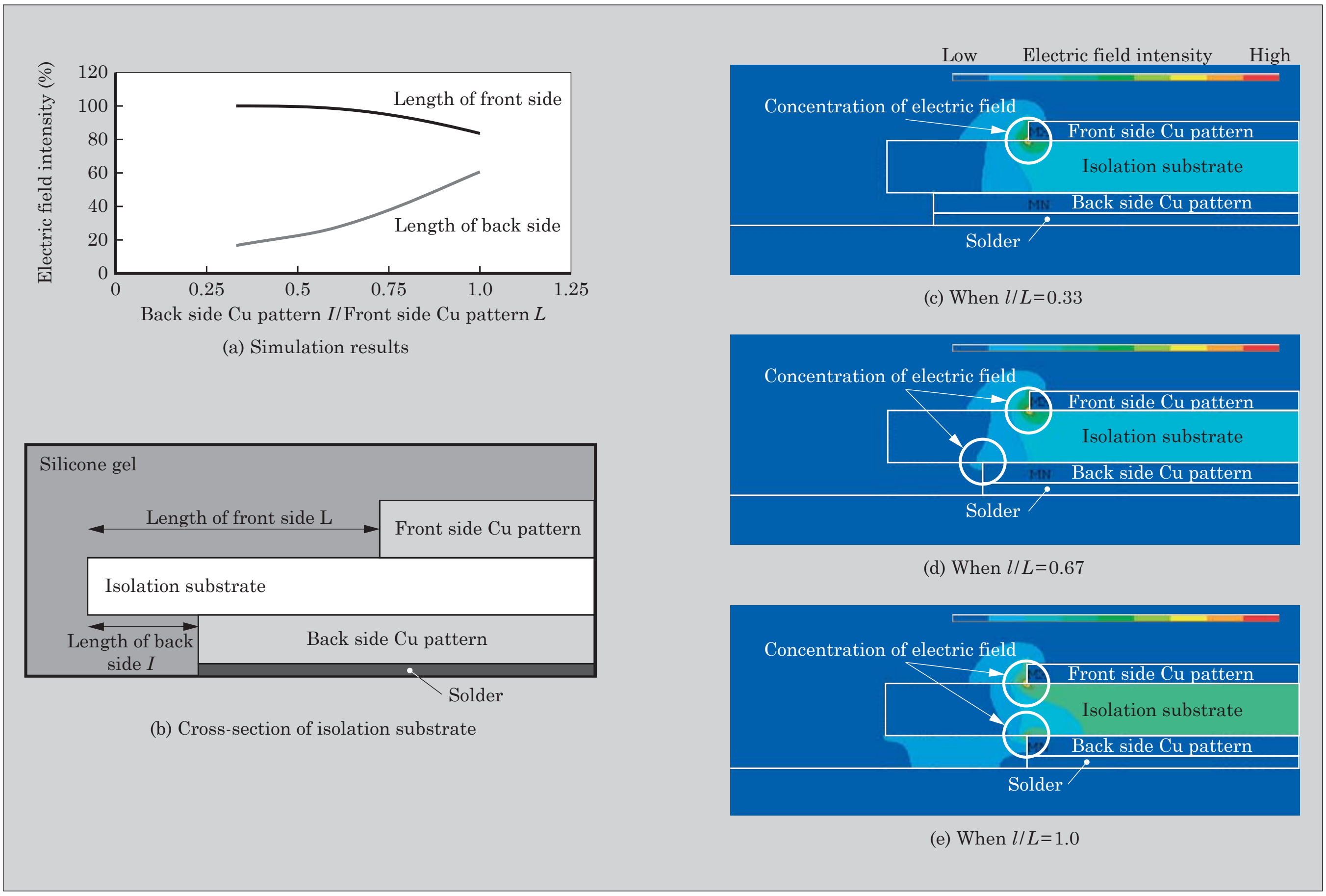

Fig.9 Simulation results of electric field intensity when isolation substrate thickness and substrate surface distance are constant

Furthermore, the process conditions for the silicone gel were optimized to improve adhesion to the isolating substrate and realize isolating voltage (6.0 kV) equivalent to that of a 3.3 kV module.

4.2 Improving the power cycle capability

This module inherits the same high power package technologies[1] as used in the currently mass-produced high power IGBT modules. The DCB (direct copper bonding) substrate is divided into separate substrates, the thermal buffering between DCB substrates is alleviated, and the module is provided with a main terminal structure that equalizes the current between the DCB substrates.

Additionally, aluminum silicon carbide (AlSiC) is used for the base plate, and in power cycle tests (ΔT_c=80 °C) that assume traction or other applications for which the high power IGBT module is intended, capability of more than 20,000 cycles was achieved.

5. Postscript

This paper has introduced Fuji Electric's high power IGBT module products that have a high isolation voltage capable of accommodating a 3-level inverter device and that are suitable for applications in the traction field. These modules are certainly capable of satisfying the needs of the new energy field, which is growing at an annual rate of 27%, and the traction field.

In the near future, Fuji Electric will begin to develop high power IGBT modules in conformance with the RoHS directive*1, and in response to further needs, intends to develop new products that will contribute to the advancement of power electronics.

*1: RoHS directive: EU (European Union) directive on the restriction of the use of certain hazardous substances in electrical and electronic equipment

Newly Developed High Power 2-in-1 IGBT Module

Takuya Yamamoto † Shinichi Yoshiwatari †

ABSTRACT

Aiming for applications to new energy sectors, such as wind power and solar power generation, which are continuing to exhibit growth, Fuji Electric has developed the new High Power 2-in-1 IGBT (insulate gate bipolar transistor) module suitable for parallel connections. This product is equipped with a new 6th generation "V Series" IGBT. Operation is guaranteed for semiconductor chip junction temperatures of up to 175 °C, and the industry's leading level of low on-voltage and low switching energy are achieved. Package technology such as ultrasonic weld-ing and high reliability lead-free solder are utilized to ensure higher reliability than ever before.

1. Introduction

IGBT (insulated gate bipolar transistor) modules are widely used because of their benefits of low power loss, high voltage tolerance, and ease with which drive circuits can be designed. In high-voltage high-power applications as well, IGBT modules are replacing GTO (gate turn-off) thyristors, which had been widely applied until now, and are being used extensively in high power inverters and high voltage inverters.

In recent years, markets for new energy (solar and wind power) have grown rapidly as part of the efforts to prevent global warming. For these applications, there is an ongoing trend of higher power capability in power conversion equipment, and there is a greatly expanded need for high power IGBT modules. Fuji Electric has a history of developing high power IGBT module products that target applications in this field.

For this new energy field, Fuji Electric has developed a new high power 2-in-1 IGBT module having an elongated structure suited for parallel connections. This product is equipped with a "V Series" IGBT, and simultaneously achieves industry-leading levels of low on-state voltage and low switching energy. Furthermore, the latest package technology is used to realize also high power density and high reliability.

This paper presents an overview and describes the performance of Fuji Electric's new high power 2-in-1 IGBT modules.

2. Product Lineup

The package appearance and product lineup of Fuji

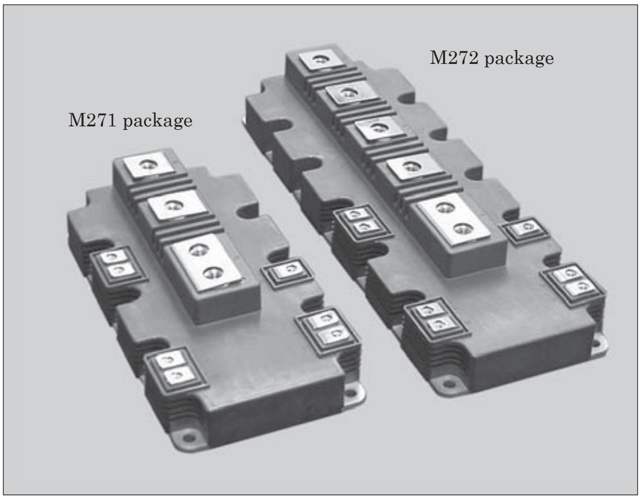

Fig.1 Appearance of new high power 2-in-1 IGBT module packages

Table 1 New high power 2-in-1 IGBT module product lineup

Product type	Package type	Package size (mm)	Rated voltage (V)	Rated current (A)
2MBI600VXA-120E-50	M271	172×89×38	1,200	600
2MBI900VXA-120P-50				900
2MBI1400VXB-120P-50	M272	250×89×38		1,400
2MBI650VXA-170E-50	M271	172×89×38	1,700	650
2MBI1000VXB-170E-50	M272	250×89×38		1,000

† Fuji Electric Co., Ltd.

Electric's new high power 2-in-1 modules are shown in Fig. 1 and Table 1, respectively. The product lineup consists of two packages for the voltages classes of 1,200 V and 1,700 V, and the modules have rated currents ranging from 600 to 1,400 A.

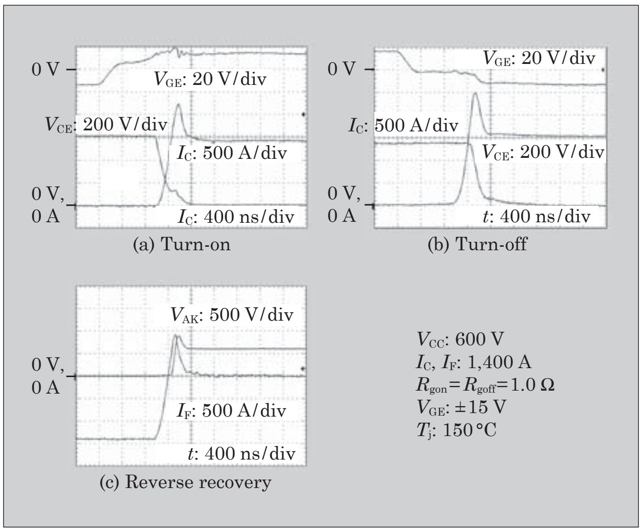

Fig.2 Switching waveform

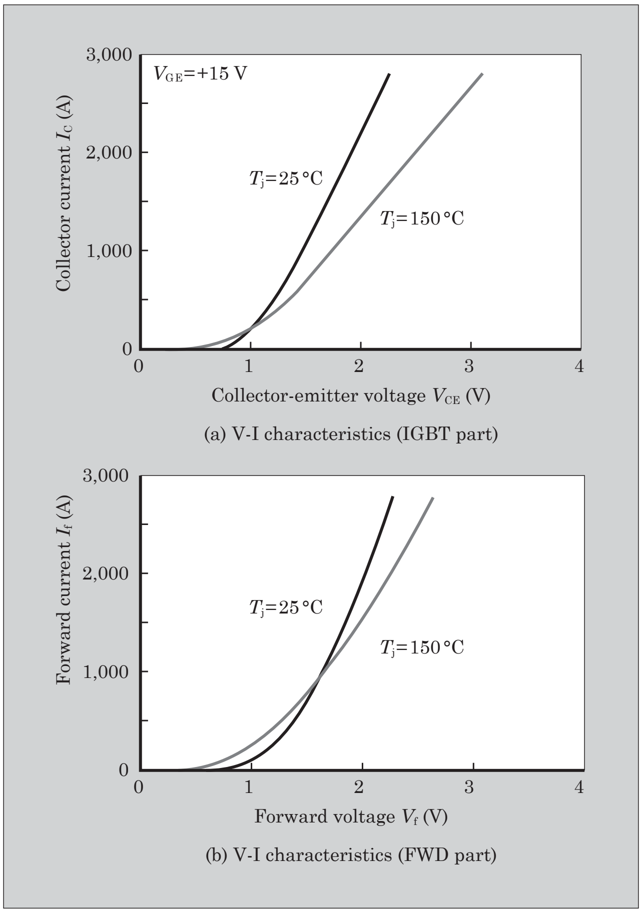

Fig.3 V-I characteristics

3. Electrical Characteristics

This product line is equipped with a V Series IGBT, and ensures a chip maximum junction temperature of T_j = 175 °C, and an operating temperature $T_{j(op)}$ = 150 °C. The electrical characteristics are introduced below using the example of the 2MBI1400 VXB-120P-50 (2-in-1 1,200 V/1,400 A) module.

3.1 IGBT chip characteristics

High power IGBT modules are used to block large currents instantaneously, and their surge voltage generated during switching is also large.

With the new high power 2-in-1 IGBT module of the 1,200 V series, IGBT chip characteristics have been adjusted for high-power applications, and as shown in Fig. 2, compared to devices for low and medium power applications, softer switching characteristics have been realized. Specifically, the silicon thickness, rate of hole injection from the back of the chip, and the chip area have been optimized to realize low saturation voltage and low off-state surge voltage, which are essential performance characteristics for a high power IGBT module.

3.2 V-I characteristics

Fig. 3 shows the V-I characteristics of the module. Both the IGBT and FWD (free wheeling diode) have positive temperature coefficients and their on-state voltage increases as their junction temperatures rise.

A positive temperature coefficient has characteristics well suited for parallel connections, and indicates that the module operates to self-regulate current imbalances that occur among modules.

3.3 Switching characteristics

Fig. 2 shows turn-on, turn-off and reverse recovery waveforms of a module at the rated current of 1,400 A and under the conditions of V_{cc}=600 V, R_{gon}=R_{goff}=1.0 Ω and T_j=150 °C. These waveforms are favorable, without the occurrence of a large generated surge voltage that exceeds the rated voltage. In addition, Fig. 4

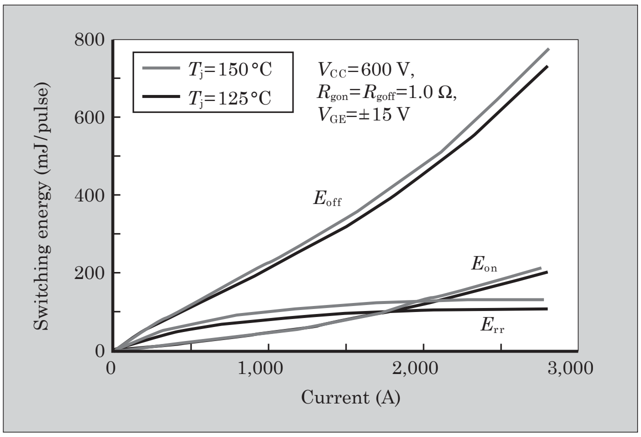

Fig.4 Current dependence of switching energy

shows the current dependence of switching energy under the same operating conditions.

4. Package Structure

Most power conversion systems used in the new energy field and elsewhere achieve high power through parallel connects of multiple modules. Moreover, in this field, a high level of reliability is required in order to supply power stably[1]. For the new high power 2-in-1 IGBT modules, an elongated package structure, as shown in Fig. 1, is selected so as to facilitate parallel connections with a bus bar. As will be described later, various improvements have been made to achieve high reliability. Additionally, in response to environmental concerns, the package has also been made with lead-free materials. Fig. 5 shows a schematic cross-sectional view of the new high power 2-in-1 IGBT module.

4.1 Application of ultrasonic terminal bonding technology

Fig. 6 shows the external appearance and a cross-sectional view of a terminal that has been attached by ultrasonic bonding. This product uses an ultrasonic terminal bonding method to bond a copper terminal directly to a copper circuit pattern. In a soldered bond structure, formed with the conventional method for bonding copper terminals, due to different coefficients of thermal expansion for the solder material and the copper material, the concentrations of stress was greatest in the solder layer. As a result, defects would occur whereby cracks would form in the solder layer and the copper terminal could be pulled off. Fig. 7 compares the results of tensile strength tests for copper terminals before and after thermal cycle tests (repeated test conditions of −40 to +150 °C). For a conventional solder bond, after 300 cycles, an approximate 50% reduction in tensile strength compared to the initial state was verified. With ultrasonic bonding, however, absolutely no decrease in tensile strength compared to the initial state was observed after 300 cycles. With the ultrasonic terminal bonding technology used in this product, copper terminals are bonded directly onto a copper circuit pattern and therefore there is no difference in the coefficient of thermal expansion at the adjoining surfaces. As a result, a significant improvement in the above-mentioned thermal cycle tolerance was achieved.

4.2 Application of highly reliable lead-free solder

In the solder layer existing between the copper base and the copper pattern under the substrate, as shown in Fig. 5, cracks form due to stress generated by

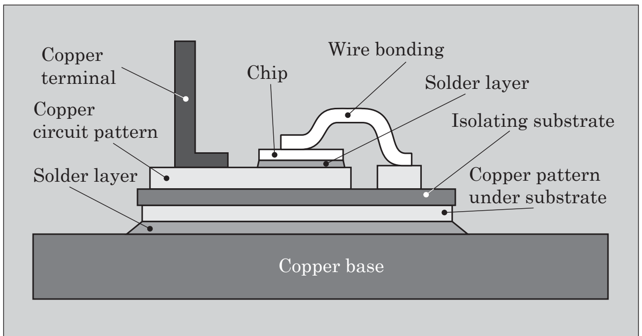

Fig.5 Schematic cross-section of new high power 2-in-1 IGBT module

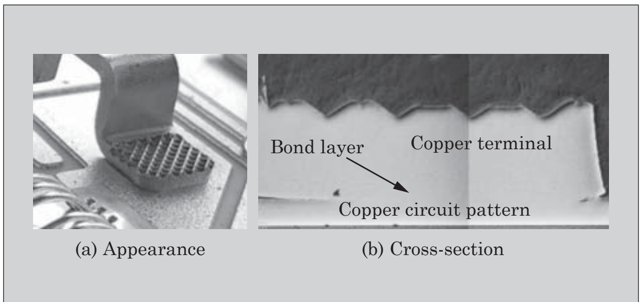

Fig.6 Appearance and cross-section of ultrasonic terminal bond

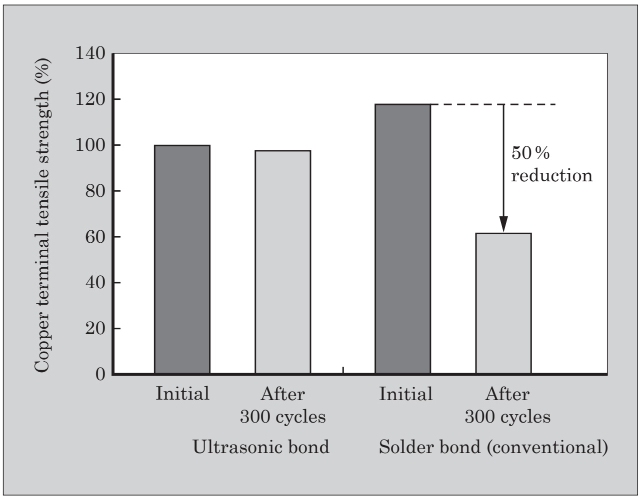

Fig.7 Copper terminal tensile strength test results

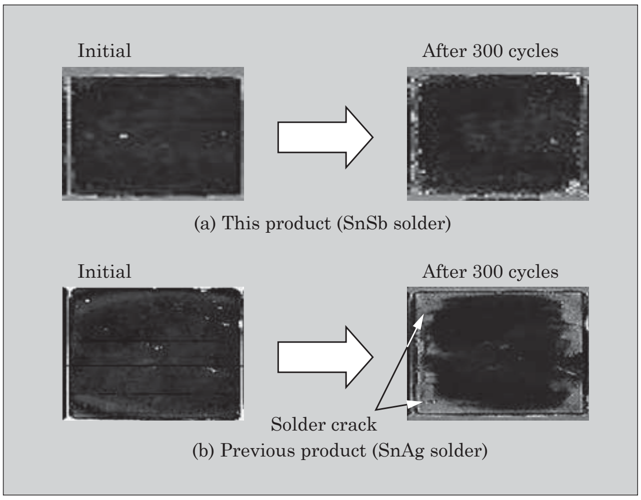

Fig.8 Results of ultrasonic crack inspection underneath isolating substrate

thermal cycling, as has been described in section 4.1. This product uses SnSb solder which is highly resistant to cracking to realize high thermal cycle tolerance. Fig. 8 shows the results of an ultrasonic crack inspection underneath the isolating substrate before and after 300 cycles of a thermal cycle test.

Compared to the conventional SnAg solder that cracked after 300 cycles, the SnSb solder used in this product exhibited almost no signs of cracking after 300 cycles. As a result of the improved solder material, greater tolerance to repeated thermal cycles (ΔT_c power cycles) that simulate actual operation was achieved as shown in Fig. 9. This new product is capable of withstanding 10,000 cycles or more at ΔT_c=80 °C, which is more than two times the ΔT_c power cycle tolerance of the prior product.

4.3 Improved environmental durability of molded case

In the state where the surface of the molded case is placed in a high electric field, particles and moisture adhering to the surface of the molded case carbonize and form conducting carbonized paths (tracks) that decrease the isolation and possibly lead to dielectric breakdown. Wind and solar power generators are sometimes installed in regions that lack a complete power infrastructure, and are often installed in high-humidity environments that contain large amounts of dust and salt. So that IGBT modules can be used with high reliability in such an environment, molded case technology that inhibits the formation of conducting carbonized paths must be developed. This product uses molding resin having a high comparative tracking index (CTI) of at least 600, thereby ensuring high tracking performance.

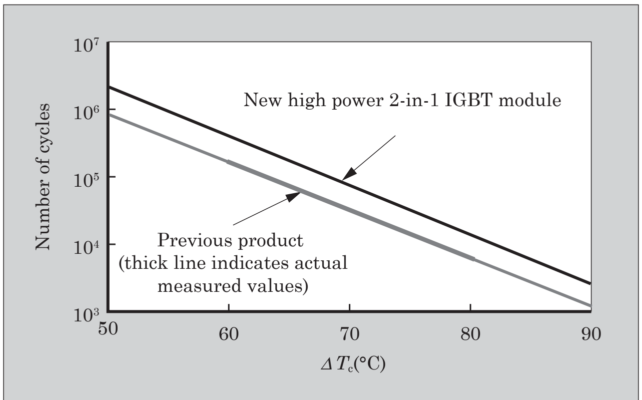

Fig.9 Tolerance to ΔT_c power cycles that simulate actual operation

4.4 Reduced stray capacitance

As described in Chapter 3, the new high power 2-in-1 IGBT module realizes electrical characteristics that are suited for high power applications. Most power conversion systems used in high power applications are required to have the capability to block large currents instantaneously. For this purpose, it is important to reduce the stray inductance within the product and to lower the surge voltage. With this product, the conducting portions of the main collector and emitter terminals are formed as flat parallel plates, and magnetic field interactions are actively utilized to reduce the internal stray capacitance from the previous value of 21 nH to 10 nH, thus achieving an approximate 50% decrease.

5. Operation With Parallel Connections

In the case where modules are connected in parallel, a reduction in reliability may result unless there is uniform current flow among the modules connected in parallel. Accordingly, it is important that current be shared evenly among modules. As mentioned above, in order to facilitate the trend toward higher power in power conversion systems, this product has electrical characteristics and a package structure suited for parallel connections. Fig. 10 shows a schematic layout

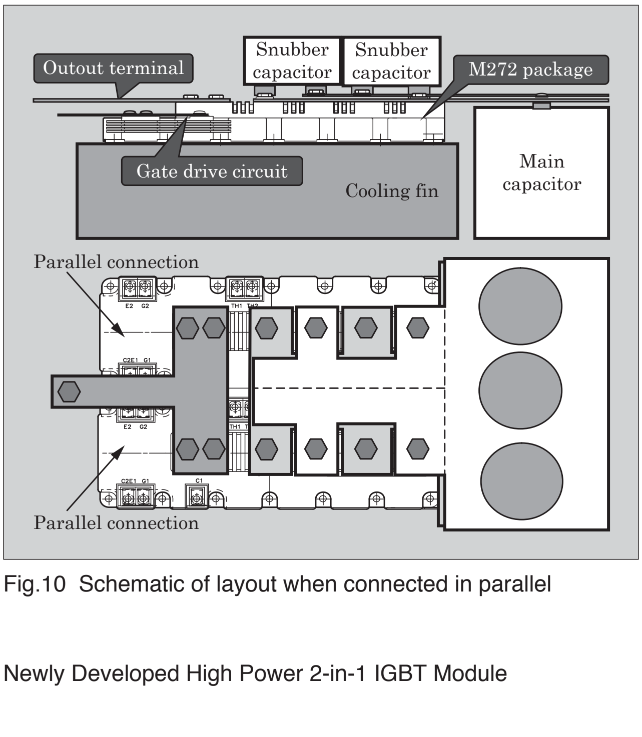

Fig.10 Schematic of layout when connected in parallel

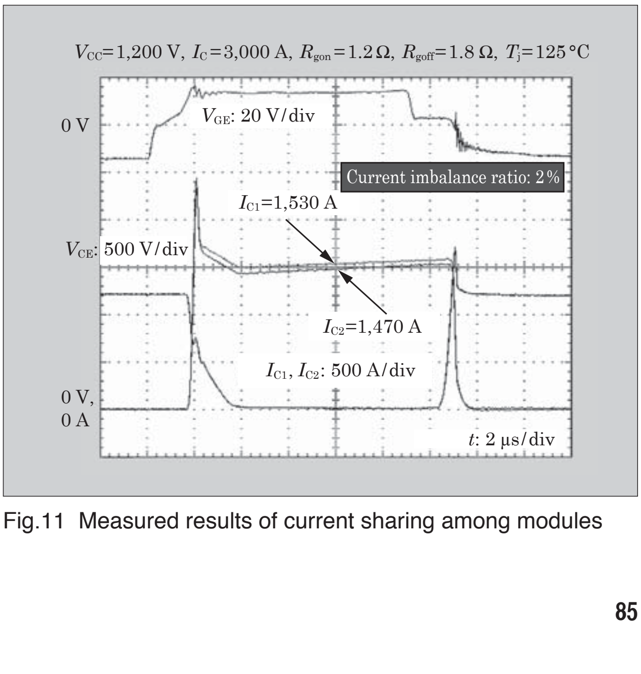

Fig.11 Measured results of current sharing among modules

of the M272 package when two modules are connected in parallel. Fig. 11 shows examples of actual measurements when two modules are connected in parallel. These measurements show favorable parallel connection characteristics with a current imbalance among modules of less than 2%.

6. Postscript

This paper has described Fuji Electric's new high power 2-in-1 IGBT module equipped with a "V Series" IGBT and featuring significantly improved reliability. These modules will certainly represent a product group capable of supporting a wide range of applications in the new energy field for which a market has been growing rapidly, as well as applications in the high power field in which needs are diversified.

In order to meet further needs in the future, Fuji Electric intends to continue to improve its semiconductor technology and package technology and to develop new products that contribute to the advancement of power electronics.

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750 V IGBTs for Mild Hybrid Vehicles

Toshiyuki Matsui † **Hitoshi Abe** † **Hiroaki Ichikawa** †

ABSTRACT

In mild hybrid cars, 600 V IGBT (insulated gate bipolar transistor) modules have often been used. Recently, however, in order to improve fuel efficiency and acceleration performance further, there has been growing demand for higher system voltages. In response to this demand, Fuji Electric has developed a 750 V IGBT and FWD (free wheeling diode) chip, and an IGBT module. A prototype of the module was evaluated and the following results were obtained. The module can be used safely with systems having power supply voltages of up to 500 V even when surge voltage is superimposed. When the 750 V IGBT is utilized, total loss can be decreased by approximately 28% compared to 1,200 V devices.

1. Introduction

Efforts to protect the global environment by reducing CO_2 emissions are mainly being carried out through the governmental policies of countries throughout the world. CO_2 emissions in the transportation sector, which includes automobiles, presently accounts for about 20% of the total amount of CO_2 emissions. The number of registered vehicles is expected to be higher the future, mainly due to increases in developing countries. To reduce CO_2 emissions, there is an urgent need to increase the proportion of environment friendly vehicles. Hybrid cars are highly practical and have the potential to contribute significantly as environment friendly vehicles. With governments and municipalities incentivizing the introduction of hybrid cars, as well as the development of hybrids to multiple types of vehicles by automobile manufacturers, expansion of this market is expected in the future.

Fuji Electric's 1,200 V IGBT-IPM (insulated gate bipolar transistor intelligent power module) for use in boost converters and 1,200 V chips having a plated structure for double-side cooling that are installed in LEXUS*[1] models LS600h and RX450h that have been commercialized for use in hybrid cars are highly regarded. In systems that use 1,200 V chips, the battery voltage is boosted and the DC voltage is increased to improve the output and efficiency. Moreover, in systems not requiring voltage boosting, such as mild hybrid systems, 600 V chips are used. Recently, however, boosting of the battery voltage or boosting of the output current has been requested even in systems that do not require voltage boosting. Intermediate-voltage IGBTs are used in such applications and are the optimal solution for applications in which 600 V chips provide an insufficient margin of voltage blocking capability, but 1,200 V chips would provide too great of a margin and would be over-spec.

Fuji Electric has accumulated experience with two series (600 V and 1,200 V) of automotive IGBT products. To meet the needs of our customers, Fuji Electric has additionally established and developed a new 750 V series as an intermediate-voltage series. The 750 V series of chips has been optimized by designing the active area, the edge termination area and the Si crystal specifications for intermediate voltages so as to maintain the high-speed and low-loss characteristics of 600 V chips, combined with the proven stable voltage blocking performance of 1,200 V chips.

2. Overview of Development

2.1 Need for 750 V series of IGBTs

Fig. 1 shows schematic diagrams of motor driving systems. Fig. 2 shows the applicable range of each voltage class of IGBT modules in terms of the relationship between maximum motor output and system voltage.

In a mild hybrid system, the system shown in Fig. 1(a) is widely used. In this system, DC current from the battery is converted into AC current by an inverter to drive a three-phase AC motor. In this case, the battery voltage is the system voltage. When using a motor of maximum output 30 kW or less, which is mostly used with mild hybrid systems, the system voltage is commonly set at 300 V or less, and 600 V IGBT modules are generally used.

On the other hand, in the case of a relatively large motor output of about 100 kW, the system of Fig. 1(b)

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*1: LEXUS is a trademark or registered trademark of Toyota Motor Corporation.

is typically used to avoid an increase in motor current. In this system, since the battery voltage of 300 V is boosted to 600 V or more, a 1,200 V series IGBT module is used. Recently, however, improved fuel economy and acceleration performance have been requested of mild hybrid vehicles.

In electric vehicles, increasing the battery to extend the travel distance will result in the vehicle becoming heavier. To drive such heavy vehicles, increased motor output is being requested. To increase the motor output without using a booster system requires that the battery voltage be increased. This corresponds to the intermediate voltage region in Fig. 2, and system voltages in the 400 to 500 V range presented a challenge in that a 600 V module would provide insufficient voltage blocking capability, while a 1,200 V module would result in excessive generated loss in the chip. Thus, Fuji Electric developed a 750 V IGBT chip and IGBT module that provide intermediate voltage blocking capability compared to the 600 V and 1,200 V models.

2.2 Chip design objectives

The design objectives of the new 750 V series IGBT and FWD (free wheeling diode) chip were set as follows to solve the challenge described in section 2.1.

- ○ Guaranteed voltage blocking capability:
  At room temperature or above, 750 V or higher
  At −40 °C, 650 V or higher
- ○ Switching loss: 600 V chip +20% level
- ○ System voltage: 500 V
- ○ High reliability for automobile use

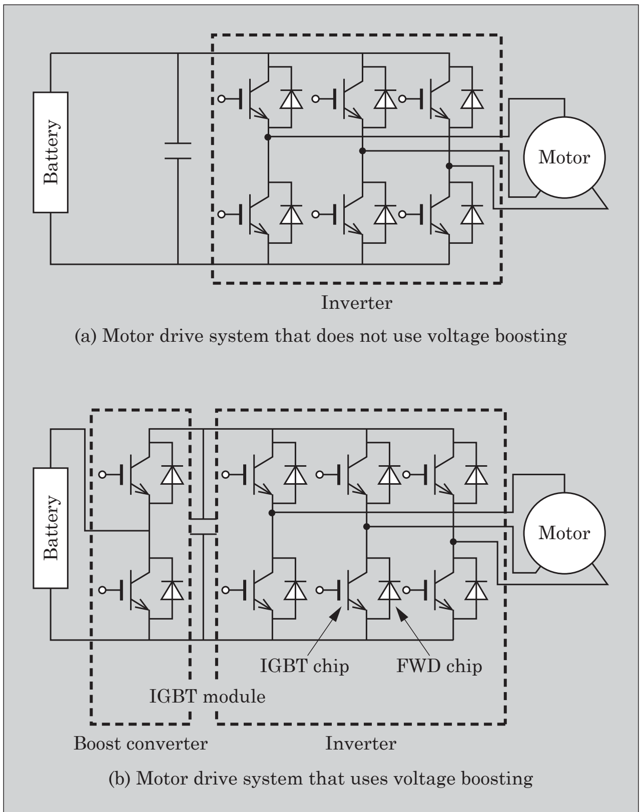

Fig.1 Schematic of motor drive system

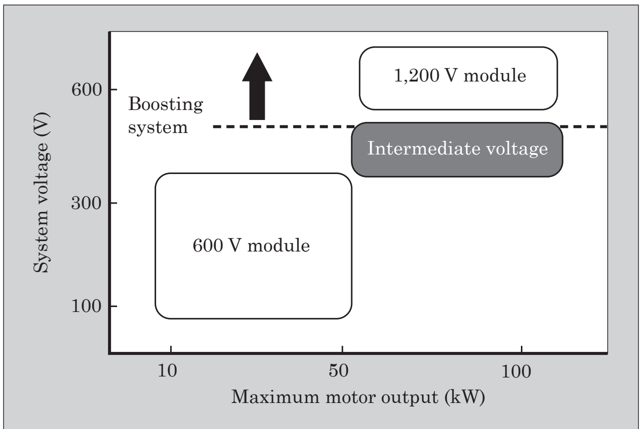

Fig.2 IGBT module application map per voltage class

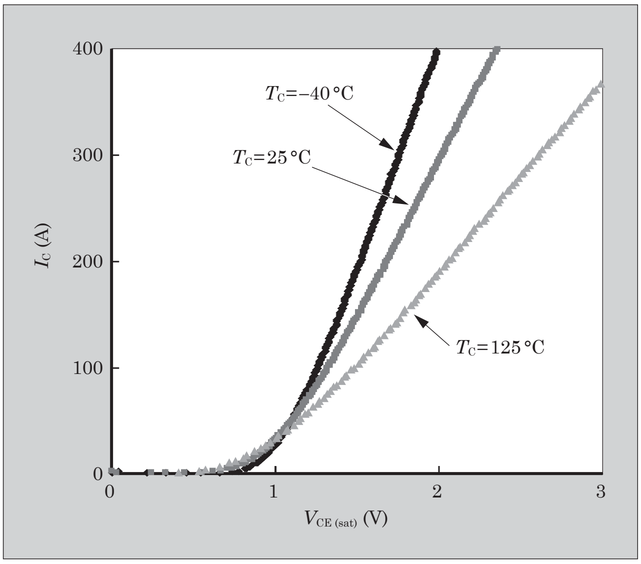

Fig.3 Output characteristics of 750 V/200 A IGBT chip

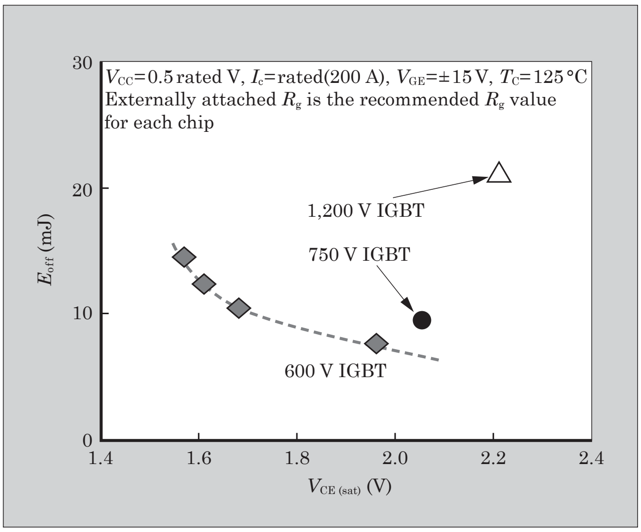

Fig.4 E_{off}–$V_{CE(sat)}$ characteristics of IGBTs for various blocking voltages

3. IGBT and FWD Chip Characteristics

The 750 V chip was designed by incorporating technology from both the 6th generation “V Series” 1,200 V chips and 600 V chips currently being mass-produced.

3.1 IGBT chip

IGBT chips are typically designed by separating the edge termination area required for ensuring the voltage blocking capability of the chip peripheral components and the active area for conducting or blocking current flow, and optimizing the design of each area and then combining them. The edge termination of the 750 V chip is based upon the proven success of Fuji Electric’s 1,200 V automobile-use chips, and was designed so as to be realized in as small an area as possible. The design was made using a device simulator to optimize the electric field distribution to achieve high reliability. Moreover, by using a high density cell structure, which has a proven track record with 600 V chips, and a FS (field stop) structure in the active area, the Si wafer is made as thin as possible and the design is optimized for 750 V use to realize a switching loss that is close to that of the 600 V chip. Fig. 3 shows the output characteristics and Fig. 4 shows the turn-off loss E_{off} vs. $V_{CE(sat)}$ characteristics, respectively, of the 750 V chip.

Additionally, Fuji Electric has also developed an IPM-use IGBT chip that contains an on-chip temperature sensing diode and a built-in current sensing function capable of sensing abnormal conditions and implementing protective operations in cases where the temperature, current or the like become excessively large.

3.2 FWD chip

As in the case of the IGBT chip, the FWD chip was also designed with a separate edge termination area and active area. However, because the resistivity of the Si crystal used in the FWD differs from that of the IGBT, the edge termination area had to be designed independently. The edge termination of the FWD is de-

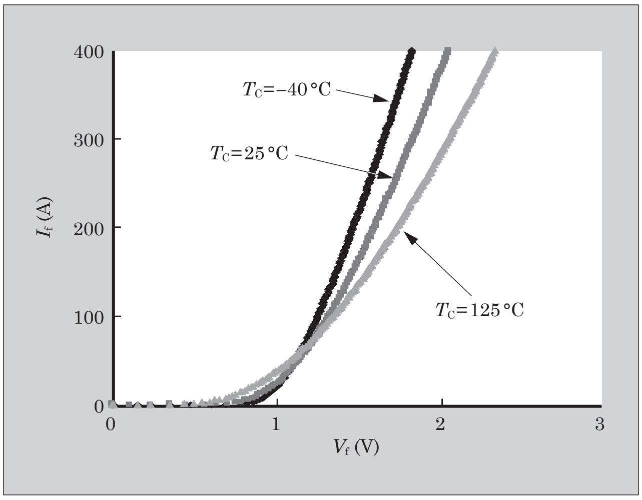

Fig.5 Output characteristics of 750 V/200 A FWD chip

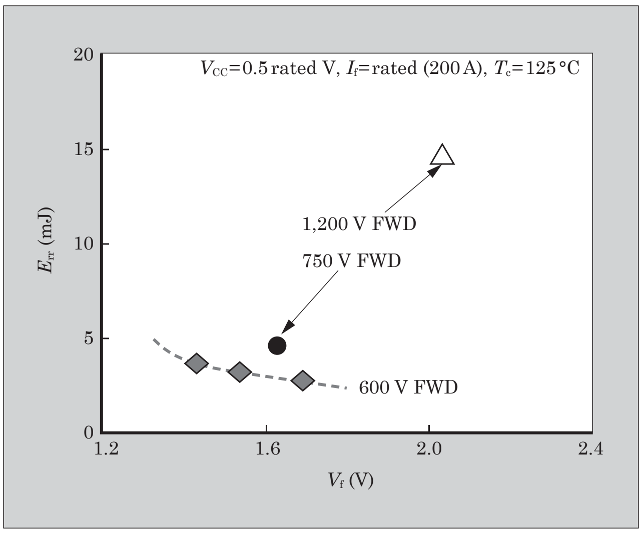

Fig.6 E_{rr}–V_f characteristics of FWDs for various blocking voltages

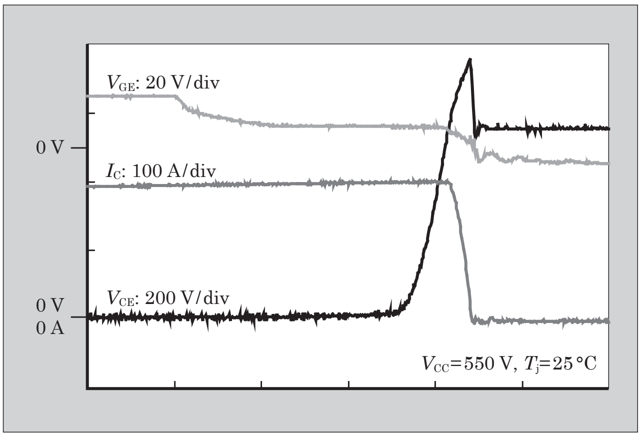

Fig.7 Switching waveform of 750 V IGBT chip

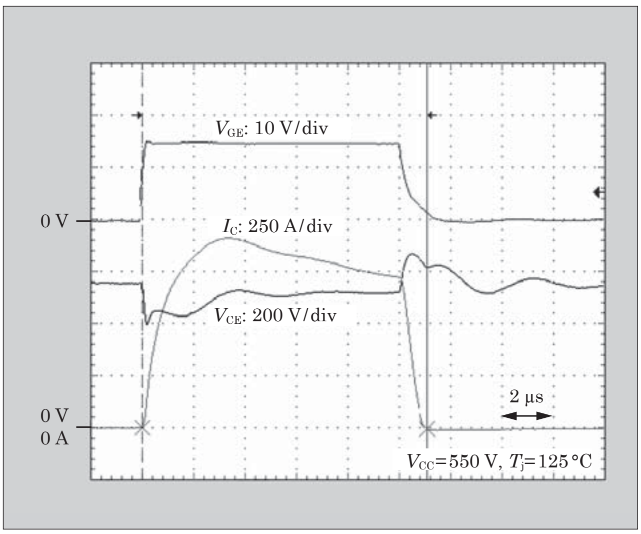

Fig.8 Short-circuit waveform of 750 V IGBT chip

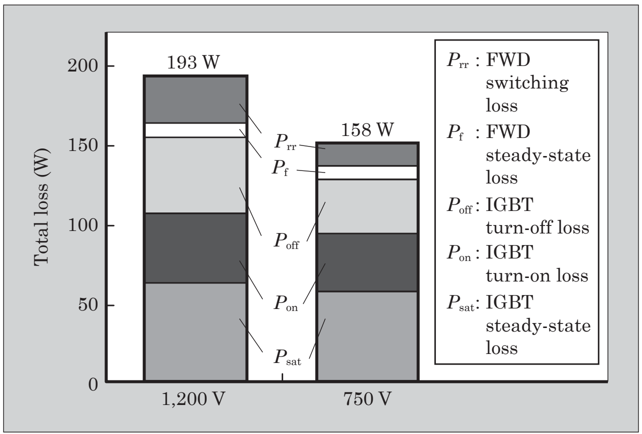

Fig.9 Comparison of module loss when motor is driven

signed based upon the proven track record of Fuji Electric's automobile-use 1,200 V chip. For the active area, the resistivity and thickness of the Si wafer, and the amount of minority carrier injection were optimized to reduce loss. As a result, reverse recovery loss E_{rr} vs. forward voltage V_f characteristics, that are close to those of the 600 V chip, were obtained. Fig. 5 shows the output characteristics and Fig. 6 shows the E_{rr} vs. V_f characteristics, respectively, of the FWD chip.

3.3 750 V module

A prototype module was built using an IGBT and FWD optimized for ensuring 750 V voltage blocking, and the characteristics were evaluated as follows. Fig. 7 shows the turn-off waveform when driven by a DC voltage of 550 V. Although dependent upon the inductance of the DC smoothing circuit and the snubber circuit design, in this example, the surge voltage rose to nearly 750 V, indicating that 750 V voltage blocking capability is needed. Moreover, Fig. 8 shows the waveform of a short-circuit test at the DC voltage of 550 V. Because this test is non-destructive, even if blocking begins 10 μs after the start of the short-circuited state, the module was found to have sufficient capability to withstand short-circuits. Thus, in consideration of a given margin, this device can be used safely with systems having supply voltages of up to 500 V.

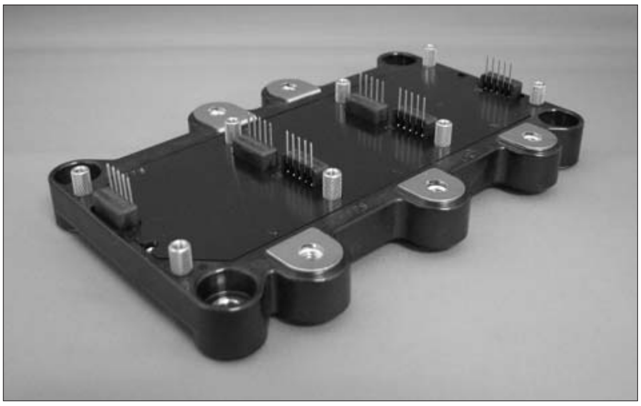

Fig.10 External view of 750 V/200 A inverter module

The generated loss when operating the inverted was estimated from the aforementioned evaluation results of the prototype inverter module characteristics. As shown in Fig. 9, when a motor is driven with a system voltage of 500 V, the total loss of the module was approximately 28% less than in the case when using a 1,200 V module. Fig. 10 shows the external appearance of the 750 V/200 A inverter module prototype.

4. Postscript

Through their use in a diverse range of industrial to consumer applications, the technical development of IGBT modules has continued to date, and industrial and consumer demand is not expected to diminish in the future. Meanwhile, the growth of the automobile drive sector has been remarkable, and there is no doubt that this market will rival or surpass that of conventional sectors.

As a device manufacturer, Fuji Electric considers itself obligated to continue to supply compact high-performance power devices in the automotive industry, and intends to continue to develop such devices together with its customers.

“High Speed V-Series” of Fast Discrete IGBTs

Taketo Watashima † **Ryu Araki** †

ABSTRACT

Fuji Electric has developed and commercialized the “High Speed V-Series” of discrete IGBTs (insulated gate bipolar transistors) rated at 600 V/35-75 A and 1,200 V/15-40 A for improving power conversion efficiency and downsizing of mini UPSs (uninterruptible power supplies) and photovoltaic power conditioners. IGBT chips combining low on-voltage with high-speed switching characteristics and high-speed FWD chips are mounted in a small discrete package. In simulations of application to a UPS full-bridge circuit, lower loss by about 15% with the 600 V product and about 30% with the 1,200 V product was achieved in comparison with conventional series.

1. Introduction

In response to recent wide-ranging environmental problems such as global warming and environmental destruction, there has been a heightened awareness of global environmental protection, and against this backdrop there has been a growing movement for energy savings. Meanwhile, as a result of the rapid spread of digital consumer electronics and the network capability of various electronic products, the amount of digital data transmitted through networks has increased explosively and as a result, the environment around us is changing greatly.

In the past, so that digital data on a network would be available at all times and in order to guarantee the reliability of that data, a large-size UPS (uninterruptible power supply) of 100 kVA or more was typically installed in the power supply area of a data center. Recently, however, in order to accommodate the higher densities of server equipment installations in data centers, a method of parallel redundant operation is becoming popular, whereby the installation of small-size UPSs is implement with a distributed architecture, and is combined with mini-UPS devices of approximately 10 kVA in order to improve the reliability of the power supply lines.

Further, in order to conserve resources and reduce CO_2 emissions, renewable energy is also being

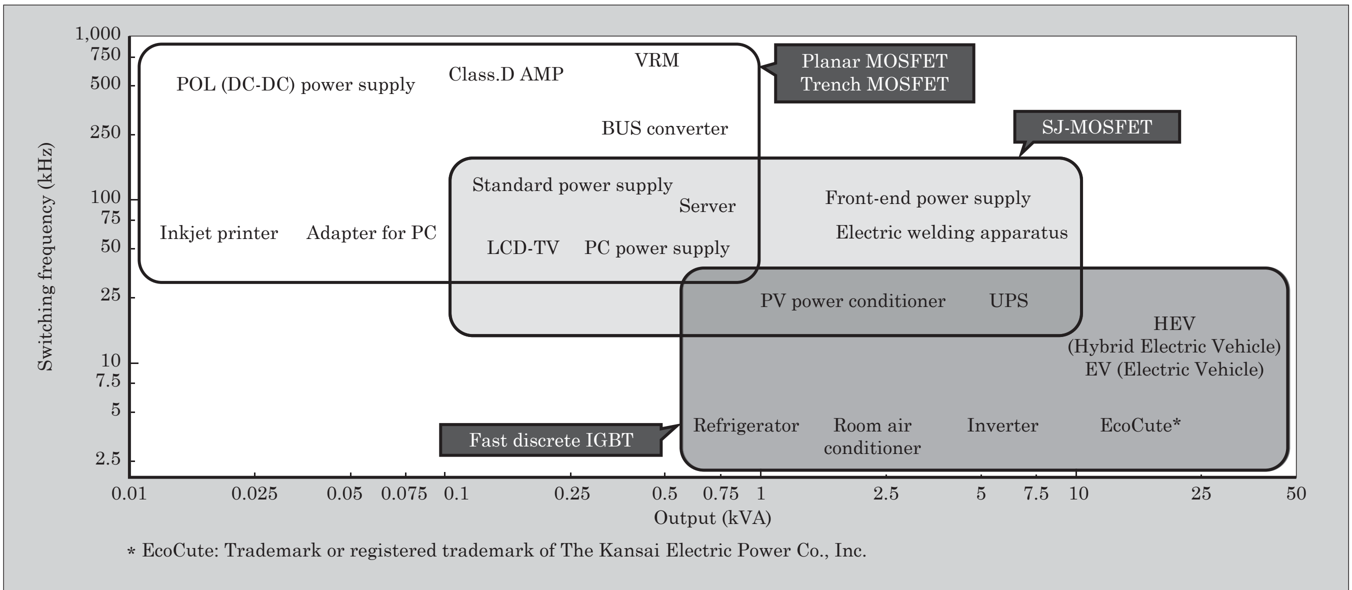

Fig.1 Major switching semiconductor devices and specifications of power supplies to which they are applied

† Fuji Electric Co., Ltd.

introduced. Among government supported initiatives for renewable energy, photovoltaic power generation systems are spreading rapidly. In these photovoltaic power generation systems, the DC power generated by solar cells must be converted into AC power, and 3 to 5 kVA power conditioners are being used as home-use power converters.

As they increase in popularity, these devices will be made inevitably with higher efficiency and smaller size as measures to counter global warming, and there is a great need for low-loss switching devices that are necessary for improving power conversion efficiency and realizing smaller size devices.

Mini-UPSs and power conditioners use discrete IGBTs (insulated gate bipolar transistors).

To improve the trade-off relation between low on-voltage characteristics and high-speed switching characteristics, and to realize higher performance and greater ease of use of mini-UPSs and power conditioners, Fuji Electric has developed a "High Speed V-Series" of fast discrete IGBTs, which are introduced herein.

2. Product Overview

Fig. 1 shows the main types of switching semiconductor devices and the specifications of power supplies to which they are applied. Major applications of the newly developed high-speed discrete IGBTs are shown in Fig. 1 and their appearance is shown in Fig. 2. Additionally, Table 1 lists the product lineup of the High Speed V Series,

The 600 V series, consisting of 35 to 75 A IGBT chips and 15 to 35 A FWD (free wheeling diode) chips, and the 1,200 V series, consisting of 15 to 40 A IGBT chips and 12 to 30 A FWD chips, are each housed in a single compact package (TO-247 package of dimensions 15.5 (W)×21.5 (H)×5 (D) (mm)), are provided with an

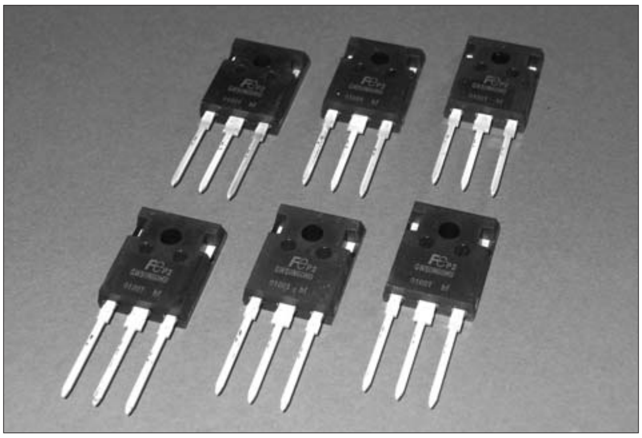

Fig.2 Appearance of "High Speed V Series" of fast discrete IGBTs

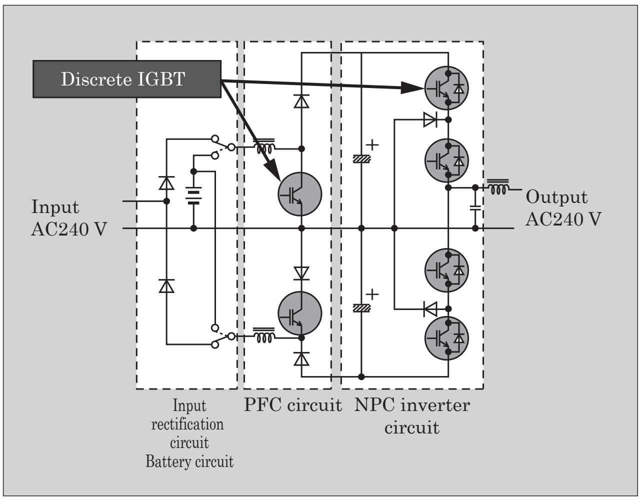

Fig.3 Typical circuit example of mini-UPS (3-level power conversion circuit)

Table 1 Major maximum ratings and electrical characteristics of "High Speed V Series"

Model	FWD type	Package	Maximum rating				Electrical characteristics			
			IGBT			FWD	IGBT		FWD	
			T_j=100 °C			T_j=100 °C	T_j= 25 °C typ	T_j= 125 °C typ	T_j= 25 °C typ	T_j= 125 °C typ
			V_{CES} (V)	I_C (A)	I_{CP} (A)	I_F (A)	$V_{CE(sat)}$ (V)	$V_{CE(sat)}$ (V)	V_F (V)	V_F (V)
FGW35N60HD	Ultra Fast FWD	TO-247	600	35	105	15	1.5	1.8	2.1	1.7
FGW50N60HD	Ultra Fast FWD	TO-247	600	50	150	25	1.5	1.8	2.1	1.7
FGW75N60HD	Ultra Fast FWD	TO-247	600	75	225	35	1.5	1.8	2.1	1.7
FGW35N60H	w/o FWD	TO-247	600	35	105	–	1.5	1.8	–	–
FGW50N60H	w/o FWD	TO-247	600	50	150	–	1.5	1.8	–	–
FGW75N60H	w/o FWD	TO-247	600	75	225	–	1.5	1.8	–	–
FGW15N120HD	Ultra Fast FWD	TO-247	1,200	15	45	12	1.7	2.1	2.3	1.85
FGW30N120HD	Ultra Fast FWD	TO-247	1,200	30	90	20	1.7	2.1	2.3	1.85
FGW40N120HD	Ultra Fast FWD	TO-247	1,200	40	120	30	1.8	2.2	2.3	1.85
FGW15N120H	w/o FWD	TO-247	1,200	12	36	–	1.7	2.1	–	–
FGW30N120H	w/o FWD	TO-247	1,200	20	60	–	1.7	2.1	–	–
FGW40N120H	w/o FWD	TO-247	1,200	30	90	–	1.8	2.2	–	–

expanded array of options so as to support UPSs and power conditioners having various outputs, and were designed in consideration of the trend toward equipment downsizing and to improve the convenience of mounting.

3. Design Policy

3.1 Application trends and device issues

Fig. 3 shows a typical example of a mini-UPS circuit.

In order to reduce power loss in a mini-UPS, an increasing number of commercialized high-efficiency UPSs has used 3-level power conversion technology in their inverters.

Fig. 4 shows a typical example of a power conditioner circuit.

A power conditioner is a device that converts the DC power generated by a photovoltaic module into AC power for home use, and as the DC-AC conversion efficiency increases, a greater amount of power can be generated and the amount of power usable at home increases. In power conditioners as well, examples of the application of 3-level inverters (see explanation on page 108) are appearing in order to achieve even high efficiency.

Fig. 5 shows the analysis results of device loss in a 3.5 kW-class UPS inverter. Of the total loss, it was found that approximately 60% is attributable to the on-voltage loss (V_{on}) and approximately 30% is attributable to the switching loss (E_{on}, E_{off}) of the IGBT. Also, in a FWD, the t_{rr} loss during the reverse recovery mode is dominant.

Therefore, the IGBTs installed in inverters are requested to have low on-voltage and, during high current and high-speed switching operation, to exhibit low loss performance (i.e., an improved tradeoff relation between $V_{CE(sat)}$ and E_{off}). Further, in FWDs, the highest priority issue is to reduce switching loss by shortening t_{rr}.

3.2 Characteristics of 600 V series of IGBT chips

Fig. 6 shows the cross-sectional structures of 600 V IGBT chips of the conventional "E Series" and the recent "High Speed V Series."

The High Speed V Series combines a trench gate structure on the front surface and a field stop (FS) structure on the back surface, and was designed to provide a significant improvement in the tradeoff relation between $V_{CE(sat)}$ and turn-off loss based on Fuji Electric's V Series IGBTs for motor drives.

Fig. 7 shows the $V_{CE(sat)}$ vs. E_{off} characteristics of a conventional 600 V/30 A IGBT and of the High Speed V Series.

For the approximate 20 kHz high-speed switching operation of a mini-UPS, power conditioner or the like, which is the targeted application of the newly developed 600 V IGBTs, the High Speed V Series has improved the high-frequency drive performance through optimizing the chip surface structure to reduce Miller capacitance and achieving a reduction in both $V_{CE(sat)}$ and E_{off} while maintaining the required breakdown tolerance for the application.

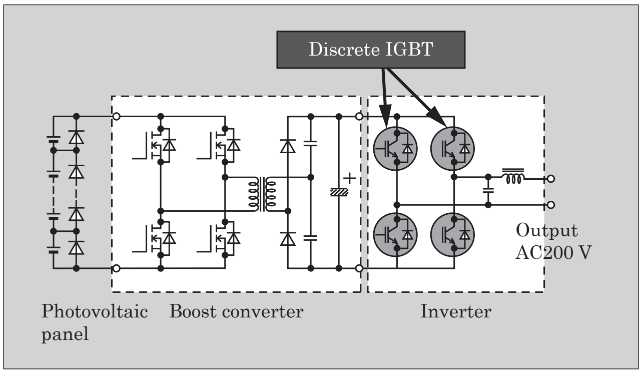

Fig.4 Typical circuit example of power conditioner

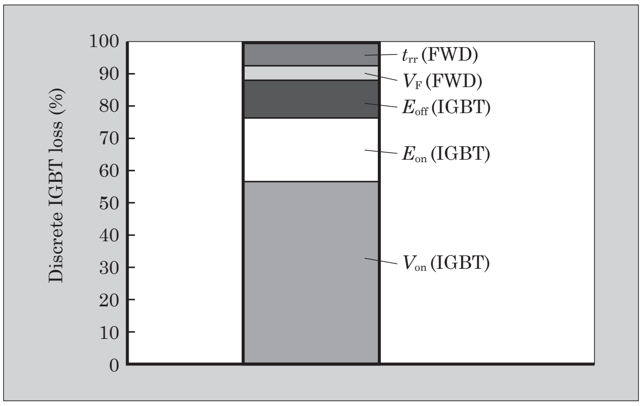

Fig.5 Analysis results of device loss when installed in 3.5 kW-class UPS

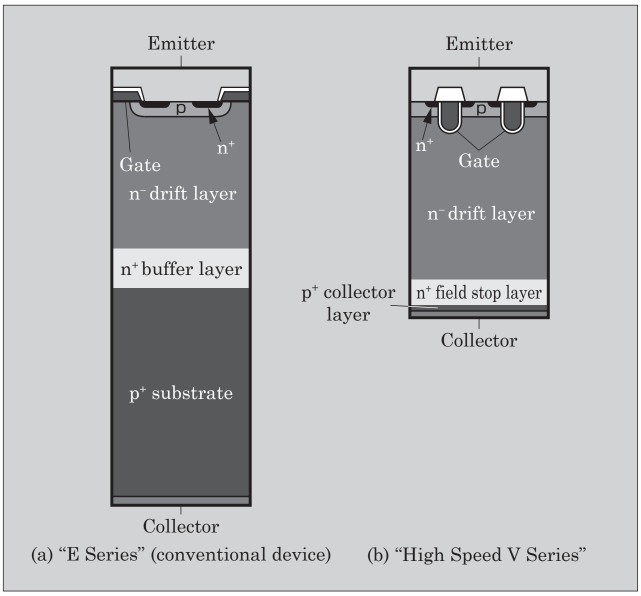

Fig.6 IGBT chip cross-section

3.3 Characteristics of 600 V series of FWD chips

The following characteristics of the 600 V FWD were optimized to reduce switching loss.

(a) Anode region impurity density
(b) Lifetime killer diffusion profile and density
(c) Drift region thickness

As a result of these measures, specifications were established for FWD chips that are faster than conventional devices while having soft recovery characteristics, and that inhibit an increase in VF.

Fig. 8 compares the switching loss in a conventional 600 V/30 A FWD with that of the High Speed V Series. An improvement of approximately 37% less switching loss was achieved.

3.4 Characteristics of 1,200 V series of IGBT chips

The design of the 1,200 V IGBTs for high voltage use, as in the case of the 600 V IGBTs, was based upon the V Series IGBT modules for motor driving, and was optimized for discrete use to realize a significant improvement in the tradeoff relation between $V_{CE(sat)}$ and E_{off}.

Fig. 9 shows the $V_{CE(sat)}$ vs. E_{off} characteristics of a conventional 1,200 V/25 A IGBT and of the High Speed V Series.

3.5 Characteristics of 1,200 V FWD chip

The 1,200 V FWD for high voltage use, owing to an improved impurity density of reqion realizes lower E_{rr}, and at the same time, inhibits oscillation and surge voltage during reverse recovery operation. Additionally, in order to enhance its reverse recovery tolerance, the anode structure that inhibits the concentration of current in the vicinity of the edges of the active region has been optimized.

Fig. 10 compares switching loss for a conventional 1,200 V/25 A FWD device and for the High Speed V Series. An improvement of approximately 26% less switching loss was achieved.

4. Effect of Application of High-Speed Discrete IGBTs

Fig. 11 and Fig. 12 show the results of simulations of generated loss in the case of installing high-speed discrete IGBTs in a general-purpose power supply. The general-purpose power supply simulates a UPS full-bridge circuit ((PWM: pulse width modulation)

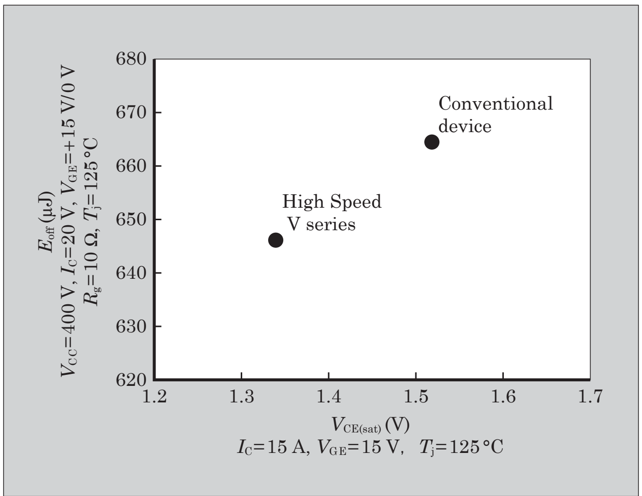

Fig.7 $V_{CE(sat)}$-E_{off} characteristics of 600 V/30 A IGBT

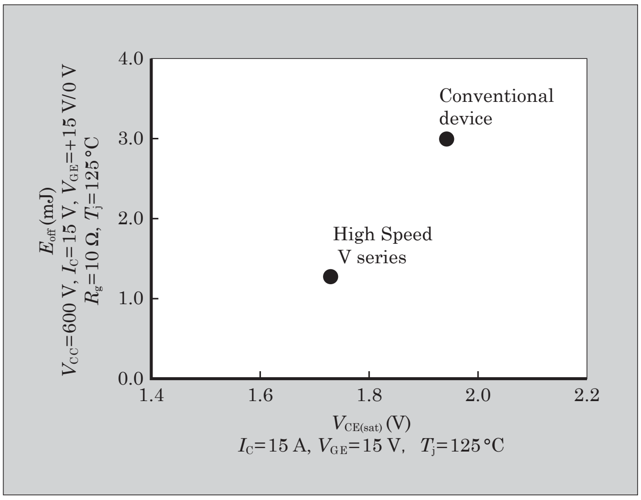

Fig.9 $V_{CE(sat)}$-E_{off} characteristics of 1,200 V/25 A IGBT

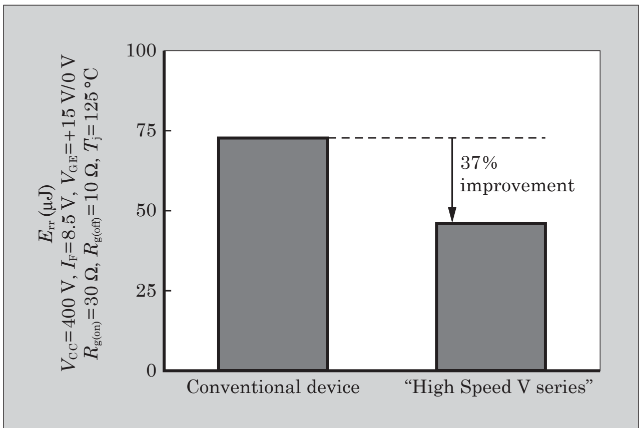

Fig.8 Comparison of switching loss of 600 V/30 A FWD

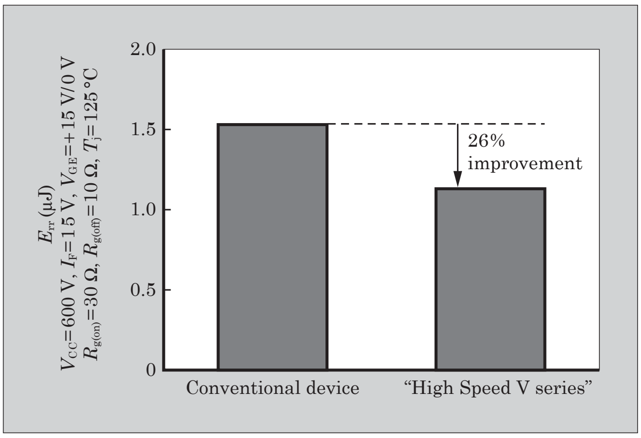

Fig.10 Comparison of switching loss of 1,200 V/25 A FWD

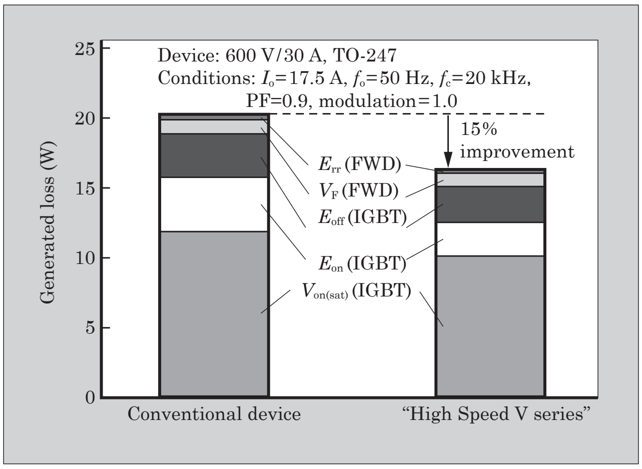

Fig.11 Loss simulation of 600 V series

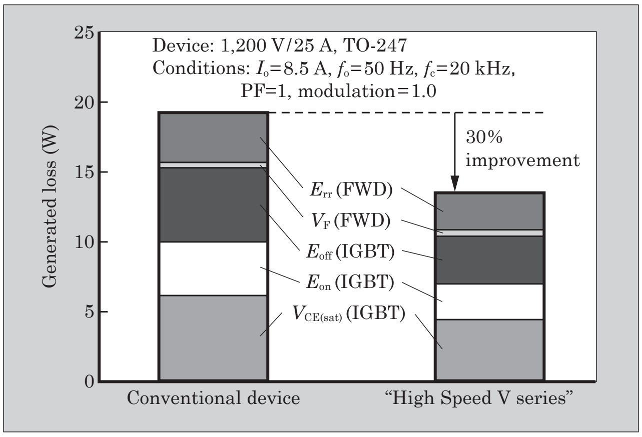

Fig.12 Loss simulation of 1,200 V series

inverter) having a 3.5 kW (200 V/17.5 A) output and 20 kHz switching frequency.

For the 600 V-class device of Fig. 11, application of the High Speed V Series is expected to reduce the total loss by approximately 15%. Moreover, for the 1,200 V-class device of Fig. 12, approximately 30% lower loss is expected. These conduction losses $V_{CE(sat)}$ of the full-bridge circuit account for about 30 to 60% of the total loss, and therefore an improved tradeoff relation between $V_{CE(sat)}$ and E_{off} will contribute to the realization of lower loss. The application of a high-speed V Series IGBT to an actual device will contribute significantly to improving the power efficiency of the overall system.

5. Postscript

These products are used not just in mini-UPSs and power conditioners for photovoltaic power generation systems, but can also be applied widely in the power supplies for small-size, low-noise machine tools such as welding (inverter welding) apparatus and laser processing machines. Fuji Electric intends to contribute to energy savings and global environmental protection through providing the marketplace with products capable of high-speed and large current switching so as to realize low loss.

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800 V Class HVIC Technology

Masaharu Yamaji [†] Masashi Akahane [†] Akihiro Jonishi [†]

ABSTRACT

To help achieve energy savings in the power systems at IDC (internet data center), 800 V guaranteed HVIC (high voltage IC) technology has been established. A proprietary device process based on self-isolation was developed. To realize energy savings in a power system, the switching efficiency of the bridge circuit used in the power system must be improved. To achieve this improvement, component and circuit technology capable of reducing the I/O propagation delay of ICs to less than 100 ns was developed. Additionally, technology for guaranteeing the ability of a HVIC to withstand the essential high d*V*/d*t* and negative voltage surges was also established.

1. Introduction

In the span of six years from 2006 through 2011 in the United States, the total power consumption of IDCs (internet data centers) has nearly doubled, which is an increase comparable to the amount of power that could be supplied by the construction of 10 new nuclear power plants.

In Japan, by 2025, the amount of information that flows through the Internet is expected to be about 200 times that of 2008, and the power consumption by IDCs will reach approximation 2.5 times the amount of 2008. Moreover, the total power consumption by ICT (information and communication technology) devices, which accounts for approximately 5% of the total power consumption in Japan in 2006, is predicted to reach approximately 20% by 2025. Initiatives to realize energy savings and higher efficiency of IDCs are an important part of the efforts to prevent global warming.

To contribute to energy savings at IDCs, Fuji Electric has developed 800 V-class HVIC (high voltage IC) technology for realizing higher efficiency, lower energy consumption, smaller size and higher reliability of IDC power supply equipment such as servers, UPSs (uninterruptible power supplies) and the like. In the development of this technology, Fuji Electric has established proprietary device process technology based upon a low-cost self-isolation process. Moreover, in order to realize energy savings in power supply systems, improvement is needed in the switching efficiency of the bridge circuit that configures the power supply system, and to realize this, Fuji Electric has also developed circuit element technology capable of limiting the I/O propagation delay time to less than 100 ns. Additionally, Fuji Electric has also established technology for ensuring the necessary high d*V*/d*t* tolerance in an HVIC. This paper introduces this device process technology and circuit element technology.

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2. Features of 800 V Class HVIC Technology

An HVIC is a high voltage IC that drives the gates of power devices arranged in a bridge circuit configuration. The intermediate potential of upper arm and lower arm power devices rises to a high potential of several hundred volts during switching of the upper arm power device, and therefore HVICs are required to be able to withstand high voltages. Moreover, compared to a conventional drive system using an optocoupler or pulse transformer, a drive system that uses a HVIC will be able to realize power supply systems that are smaller in size and more highly efficient. Fig. 1 shows

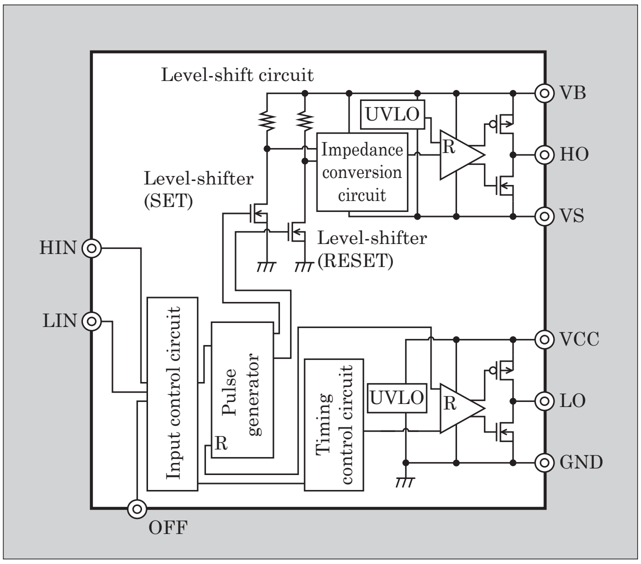

Fig.1 HVIC circuit block diagram

a block diagram of the HVIC circuit that has been developed. The HVIC is equipped with high-side and low-side drive circuits, level-shift circuit, an impedance conversion circuit, an UVLO (under voltage lock out) circuit, an input control circuit and so on.

Fig. 2 shows a self-isolation type 800 V -class HVIC chip prototype that was built for 200 V AC power supply equipment.

Features of the HVIC are listed below.

(a) Guaranteed 800 V class performance, high-side circuit power supply voltage of 30 V
(b) High-side turn on/off propagation delay time of less than 100 ns
(c) Wire bonding level-shift that applies HV wiring technology
(d) Guaranteed high negative voltage surge tolerance and d*V*/d*t* tolerance (≥50 kV/μs)

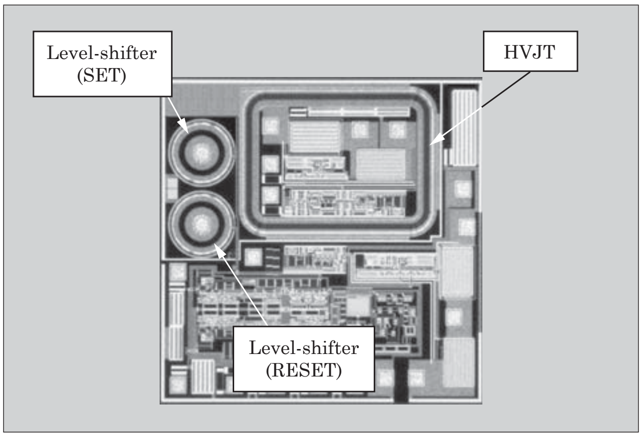

Fig.2 Self-isolation type 800 V class HVIC prototype chip

Table 1 List of 800 V class HVIC device elements

Category	Name	Intended use
Active element	7 V class LV gate low voltage n-MOSFET	Pulse generator, etc.
	7 V class LV gate low voltage p-MOSFET	
	30 V class LV gate intermediate voltage n-MOSFET	High-side and low-side output stage drivers, UVLO, latch circuit logic
	30 V class HV gate intermediate voltage p-MOSFET	
	30 V class HV gate intermediate voltage n-MOSFET	
	800 V class HVNMOSFET for level shifting	Level shift device
	30 V class NPN BJT	Internal power supply circuits, etc.
	30 V class NPN BJT	
	30 V class diode for ESD protection	ESD protection circuits, etc.
	5 V/7 V class Zener diode	
Passive element	High-resistance poly-silicon resistance	Impedance conversion circuit, etc.
	Low temperature compensation poly-silicon resistance	
	MOS capacitance	Noise filter, etc.
	Poly-silicon capacitance	

Moreover, the developed HVIC is an 800 V class device, and therefore compared to a 600 V class HVIC[(1)], when a lightning surge enters the power supply system or when used in a harsh power supply environment and noise is generated, there is the benefit in that the IC will not incur damage before the 600 V class power devices such as IGBTs (insulated gate bipolar transistors) and MOSFETs (metal-oxide-semiconductor field-effect transistors).

3. Device and Process Technology

Isolation methods for the elements that form power ICs include self-isolation, pn junction isolation and dielectric isolation. In a dielectric type HVIC, a buried oxide layer exists between the substrate and the active layer on which high-side devices and level-shift elements are formed, and as a result, this device has a smaller junction capacitance than either the self-isolation type or pn junction isolation type of IC, and is suited for high-speed performance. An additional benefit is that parasitic device malfunction and latch-up caused by negative voltage surges or the like are less likely to occur with dielectric type HVICs. However, the dielectric type HVICs presently on the market are at most 600 V class devices, and 800 V class or higher performance is technically extremely difficult to realize[(2)]. On the other hand, self-isolation type HVICs require a larger element isolation area, but have the advantages of easily increasing their breakdown voltage and of having a less expensive substrate cost.

Table 1 shows a list of 800 V class HVIC device elements. Since 30 V class intermediate voltage MOSFETs are provided as high-side devices, power device gate drive voltages can be supported over a wide range of up to 30 V. Moreover, ESD (electrostatic discharge) protection diode is ESD protection device having low-avalanche resistance and was developed to protect

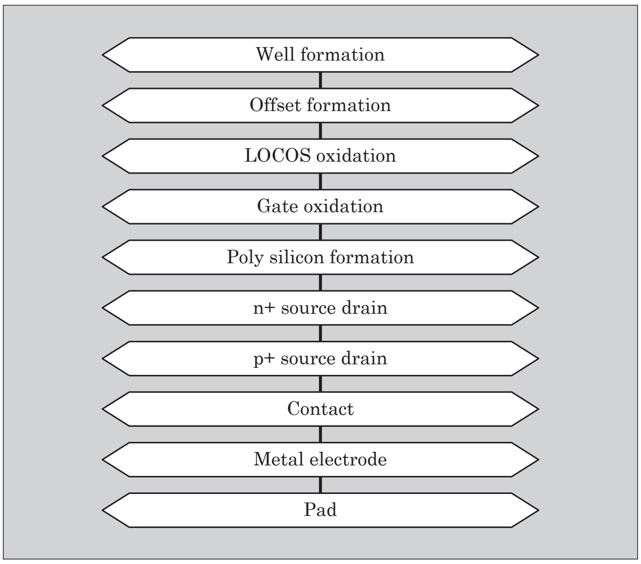

Fig.3 Process flow

the I/O pins of the IC from ESD surges at the time of package assembly and from switching noise applied to the power supply board.

3.1 Process flow

For 800 V class HVICs, the self-isolation method of Fuji Electric's high-voltage BiCMOS (bipolar CMOS) process is used. Fig. 3 shows the process flow. In this process, to form a high-voltage triple well structure provided with a deep diffused layer in the high-side drive circuit region, diffusion is performed at a high temperature for a long time during the well formation process. Additionally, process sharing among devices is being promoted to lessen the labor involved.

3.2 High-side triple well device

The design concept of the 800 V class self-isolation type devices is to use a self-isolation process to realize high tolerance against parasitic malfunction and breakdown, comparable to that of a pn junction isolation type device. A high-side triple well device was developed based upon Fuji Electric's existing high voltage processes.

Fig. 4 shows the cross-sectional structure of high-side and low-side logic devices formed on a p-type substrate (Psub). Between the high-side logic part and the low-side logic part is provided a HVJT (high voltage junction termination) region having a structure that terminates the junction between ground potential and 800 V potential. Moreover, the high-side triple well region, must be designed such that when the potential of the n-type diffusion layer (N2 diffusion layer) of Fig. 4 rises to 800 V, the depletion region extending from the junction between Psub and the N2 diffusion layer does not contact the depletion region extending from the junction between the N2 diffusion layer, which is reverse-biased to the high-side power supply voltage of 30 V, and the p-type diffusion layer (P2 diffusion layer), i.e., there will be no punch-through.

As shown in Fig. 5, the relationship between vertical direction punch-through voltage V_p and the net charge Q_n (value of P2 diffusion layer impurity concentration subtracted from N2 diffusion layer impurity concentration) of the N2 diffusion layer in a high-side

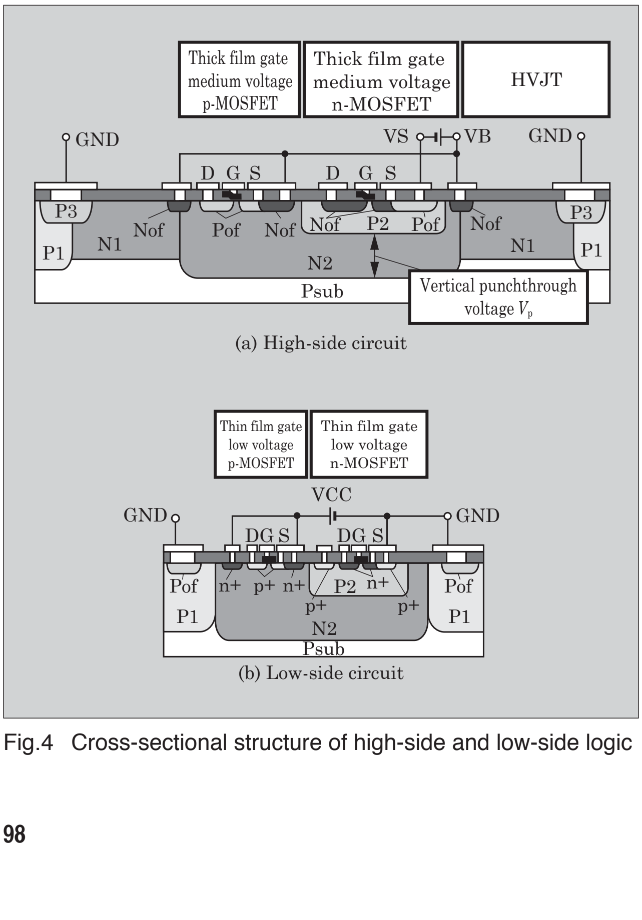

Fig.4 Cross-sectional structure of high-side and low-side logic

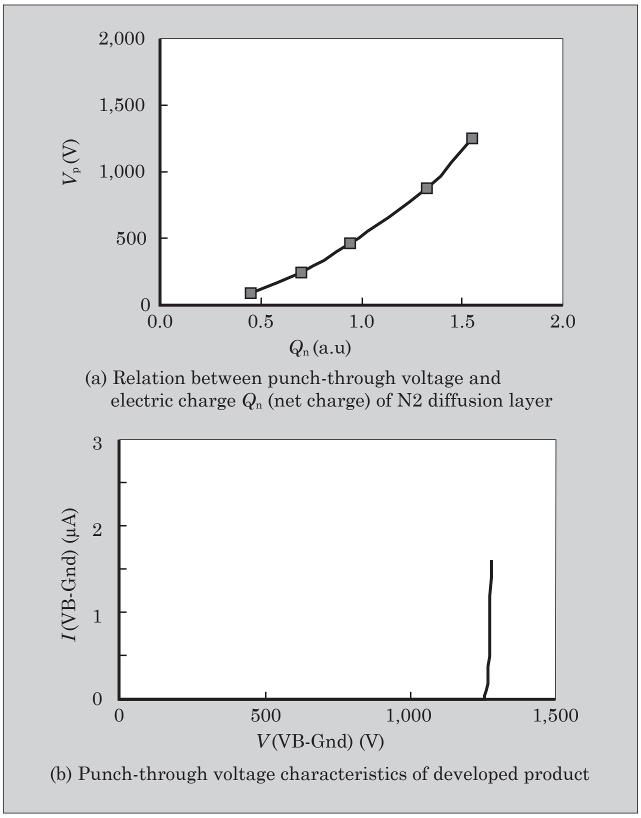

Fig.5 Relationship between vertical punchthrough voltage V_p and high-side triple well N2 diffusion layer net charge Q_n and breakdown voltage characteristics of developed product

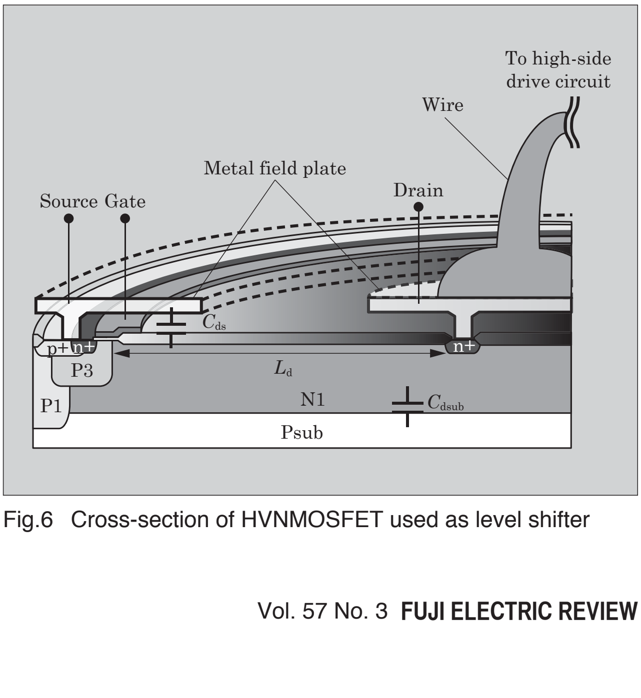

Fig.6 Cross-section of HVNMOSFET used as level shifter

triple well structure consisting of a P2 diffusion layer, a N2 diffusion layer and Psub was clarified using analysis formulas. In this design, the impurity concentrations and diffusion depths of the N2 diffusion layer and P2 diffusion layer are adjusted, and the Q_n value is adjusted so as to ensure breakdown voltage tolerance of at least 1,200 volts.

3.3 800 V class HVNMOSFET for level shifters

Fig. 6 shows the cross-sectional structure of a HVNMOSFET (high voltage n-MOSFET) used as the level shifter of Fig. 1. The SET input side and the RESET input side have the same device structure, and the HV-level shifting interconnection to the high-side drive circuit is implemented with gold wire bonding. In order to realize an 800 V class HVIC, the HVNMOSFET was devised to achieve: (1) 800 V class on-state/off-state breakdown voltage, (2) low parasitic capacitance, (3) high tolerance to parasitic action breakdown and (4) high reliability. Details are described below.

(1) 800 V class on-state and off-state breakdown voltage

By optimizing the concentration and drift region length L_d of the N1 diffusion layer, i.e., the diffusion layer shown in Fig. 6, breakdown voltages of at least 830 V could be achieved in both the on-state (V_g=5 V) and the off-state (V_g=0 V). (See Fig. 7.)

(2) Low parasitic capacitance

Among the parasitic capacitances of the HVNMOSFET, the value of C_{dsub} is determined by the necessary area of the voltage breakdown structure. C_{ds} depends on the metal field plate pattern of the source-side. Adjusting the field plate length on the source side contributed to a reduction of C_{ds} and a shorter high-side propagation delay time.

(3) High tolerance for parasitic action breakdown

Because ESD surges and dV/dt noise entering the reference potential pin of the HVIC are also applied to the drain of the HVNMOSFET, the avalanche resistance of the HVNMOSFET itself must be improved and parasitic action due to displacement current must be suppressed. The pickup structure of the source layer and base layer of the HVNMOSFET has been innovated, and ESD tolerance that sufficiently satisfies the standards, and dV/dt resistance of 50 kV/μs or above at the high temperature of 150 °C has been ensured.

(4) High reliability

The field plate structure between the source and drain of the HVNMOSFET has been optimized to limit the effects of molding compound mobile ions and

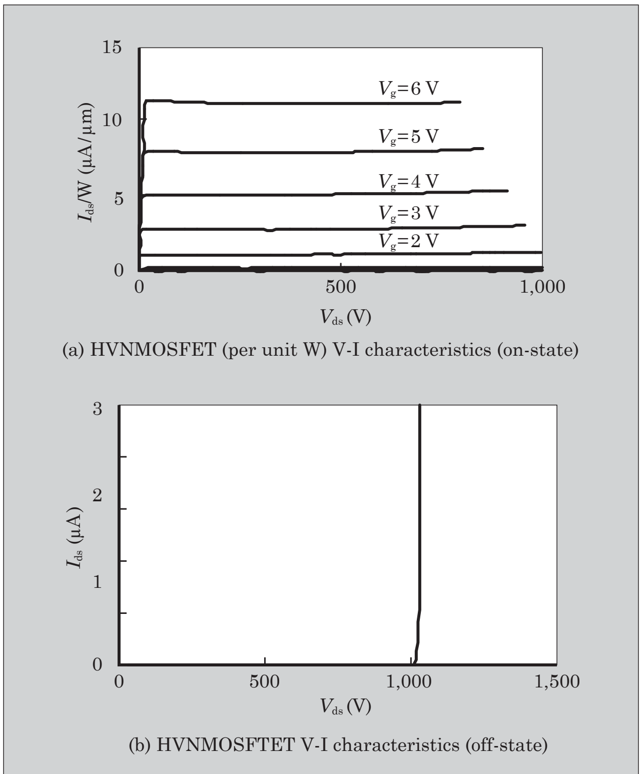

Fig.7 V-I characteristics of HVNMOSFET

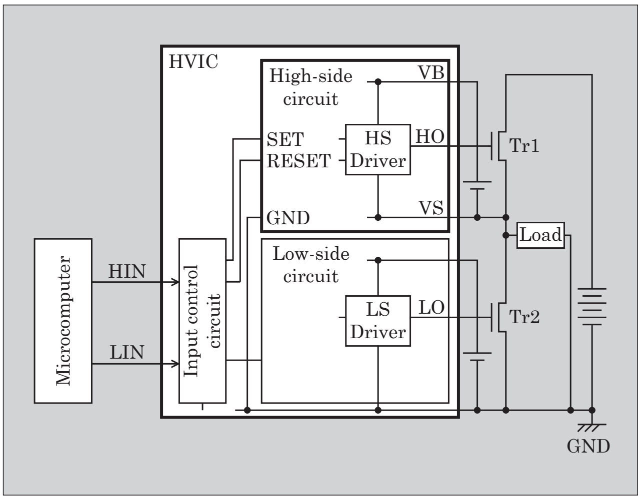

Fig.8 HVIC application example

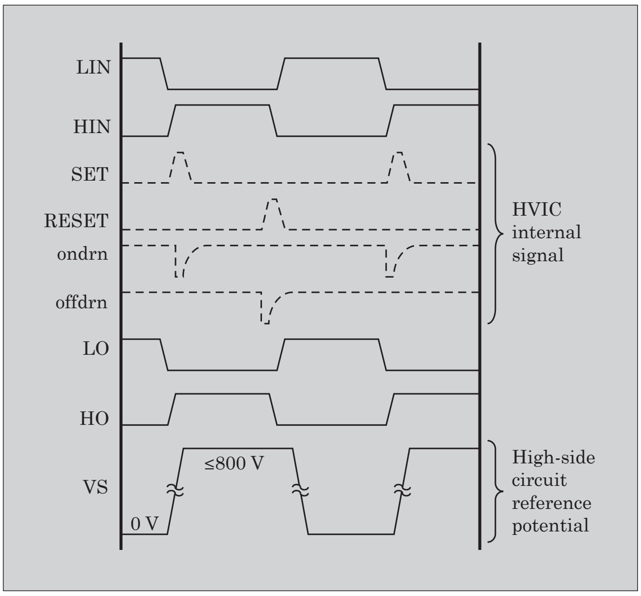

Fig.9 HIVC operation timing chart

hygroscopy on the breakdown characteristics, and high temperature bias tests, high temperature high humidity bias tests, and the like have been conducted to ensure that long-term reliability requirements are satisfied.

4. Circuit Element Technology

4.1 HVIC operation

Fig. 8 shows an example application of the HVIC. The input pins HIN and LIN of the HVIC connect to a microcomputer or the like operating at low voltage, and the output pins HO and LO connect to gate pins of an IGBT or MOSFET in a half-bridge configuration. Fig. 9 shows a timing chart of the HVIC operation. At an input control circuit, the high-side control signal HIN is converted, based upon its rising and falling edges, into the SET and RESET signals and is inputted to the high-side circuit block. Meanwhile, the low-side control signal LIN passes through an input control circuit and is input directly to the low-side circuit block.

For the high-side circuit, the output node of the half-bridge circuit is taken as the V_S reference potential. Because the V_S reference potential fluctuates between 0 and 800 V (max.) due to the alternating on-off operation of Tr1 and Tr2, d*V*/d*t* resistance to rapid rising and falling of the V_S potential and resistance to undershoot (negative voltage surge) are requested. Additionally, in order to perform highly efficient power control, reduced retardation time is being requested from the market.

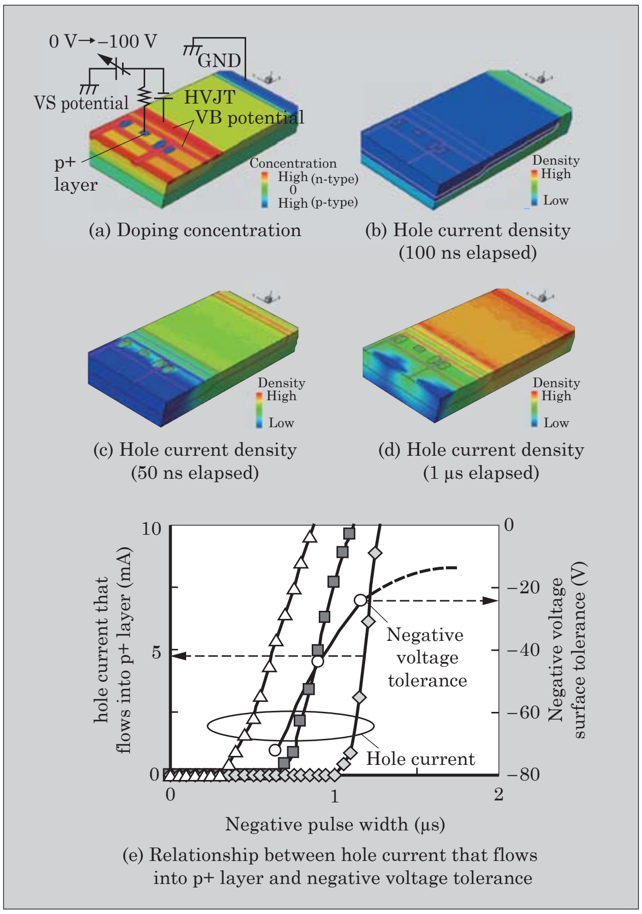

Fig.10 Example transient simulation at time of negative surge voltage generation

4.2 Negative voltage surge resistant layout design technique

As described above, the instant that the upper arm of a power device is turned off, the induced electromotive force of the load causes the V_S reference potential of the HVIC to drop several tens of volts below the reference value for a duration of several hundreds of nanoseconds. The density of the hole current that flows into the high-side circuit when the V_S reference potential is in a negative voltage state is shown in Fig. 10. Using three-dimensional transient simulations, the relationship between negative voltage pulse width and negative voltage surge resistance is quantified and reflected in the layout design.

4.3 Characteristics of high-side drive circuit

Fig. 11 shows an internal block diagram of the high-side circuit. The high-side circuit is configured from three blocks: a level-shift circuit block, a latch circuit block and a driver circuit block. The basic configuration of the level shift circuit combines resistive devices LSRs and LSRr, HVNMOSFET (SET) and HVNMOSFET (RESET) to form a common-source amplifier. To prevent malfunctions caused by fluctuation in the

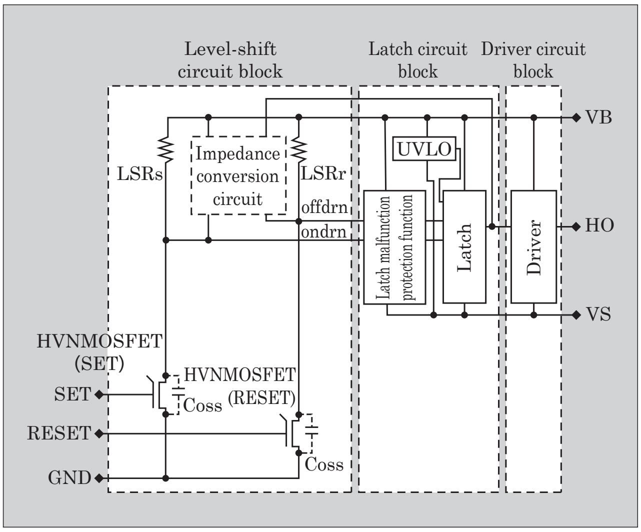

Fig.11 Internal block diagram of high-side circuit

Table 2 Function table of latch malfunction protection function

Input		Latch output
SET (offdrn)	RESET (ondrn)	
L	L	Hold
H	L	H
L	H	L
H	H	Hold

reference voltage level between 0 and 800 V (max.), an impedance conversion circuit has been devised.

The latch circuit, as shown in Table 2, is provided with a latch malfunction protection function for retaining the latch output when the SET side and RESET side signal statuses are both in the same logic state.

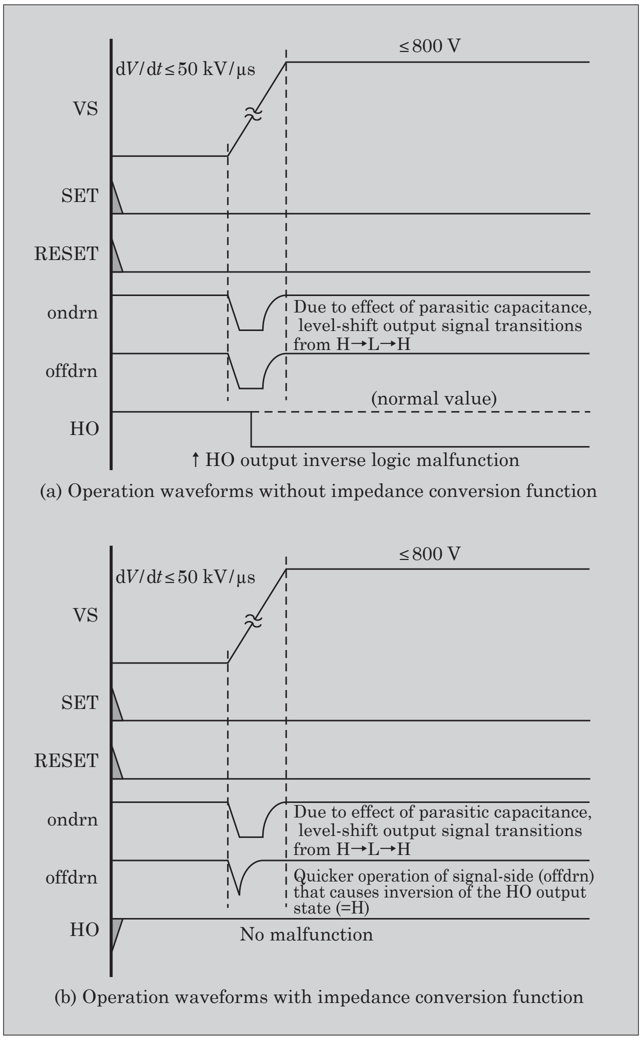

Fig.12 Operation time charts of high-side circuit when d*V*/d*t* is generated

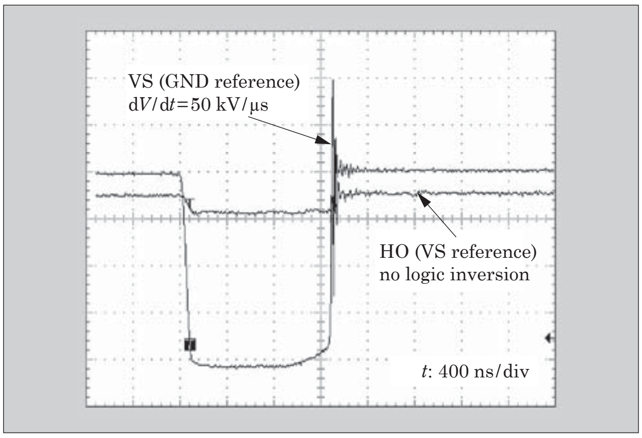

Fig.13 Measured waveforms when d*V*/d*t*=50 kV/μs

In addition, a low pass filter is provided for protecting against erroneous output when the logic level changes instantaneously due to d*V*/d*t* generation or the like. The drive circuit uses the push-pull drive method and is configured from MOSFETs having the drive capacity and dimensions that satisfy market requests for performance and the like.

4.4 d*V*/d*t* tolerance

Fig. 12 shows timing charts of the operation of the high-side drive circuit when d*V*/d*t* is generated. Fig. 12(a) shows the output states of the level-shift circuit in the case where there is no impedance conversion function. Even if the HIN input is at a low-level, the generation of d*V*/d*t* causes the V_s reference potential to fluctuate due to parasitic capacitance of the HVN-MOSFET and the d*V*/d*t*, thus generating a current flow. As a result of this current, the HVNMOSFET drain on the SET-side and RESET-side is charged and discharged and the level-shift output changes from high to low to high. As a result, the HO output is susceptible to inverse logic malfunctions. Therefore, to prevent inversion malfunctions, the high-side circuit is provided with an impedance conversion function enabling the operation shown in Fig. 12(b).

Fig. 13 shows the measured waveform when d*V*/d*t*=50 kV/ms and Table 3 lists the measured results of the temperature characteristic of the d*V*/d*t* tolerance. With the impedance conversion function, inverse logic malfunctions of the HO output were found to be prevented even when d*V*/d*t* of 50 kV/μs was generated. In addition, it was also confirmed that inverse logic malfunctions do not occur in the temperature range of −40 °C to +150 °C.

Table 3 Measured results of d*V*/d*t* tolerance in voltage range of VB=0 to 30 V

	Temperature (°C)			
	−40	25	125	150
d*V*/d*t* tolerance DC to 50 (kV/μs)	○	○	○	○

○: Inverse logic behavior does not occur

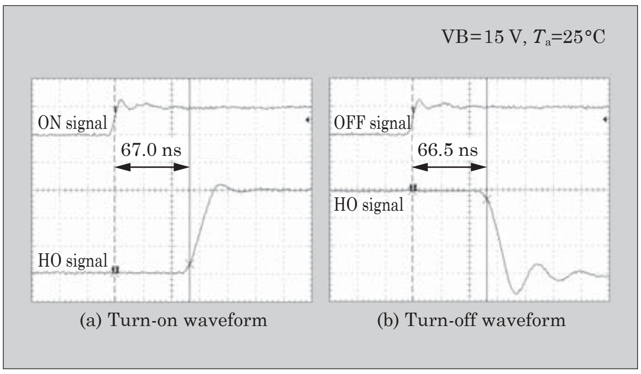

Fig.14 Measured results of turn-on and turn-off delay times

4.5 Delay time characteristics

Fig. 14 shows delay time waveforms of the high-side circuit. Fig. 14(a) shows the turn-on delay characteristics, and Fig. 14(b) shows the turn-off delay characteristics. In the voltage range of VB = 9 to 30 V, delay times of less than 100 ns were achieved.

5. Postscript

In this paper, the device, process and circuit elements technology of a newly developed 800 V class HVIC for power supply use have been introduced.

This technology not only realizes high reliability of the IC in terms of 800 V class performance and high surge tolerance, high dV/dt tolerance and the like, but through reducing the propagation time delay to less than 100 ns, also contributes to the higher efficiency, smaller size and lower cost of power supply systems. In the future, Fuji Electric intends to deploy this technology horizontally in the industrial sector consisting of general-purpose inverters, IPMs (Intelligent Power Modules) and the like, the consumer sector consisting of air conditioners, lighting and the like, and automotive sector consisting of the HID (high intensity discharge lamp) and the like.

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(2) M.Yamaji, et al, A Novel 600 V-LDMOS with HV-Interconnection for HVIC on Thick SOI. Proceedings of the 22th ISPSD. 2010, p.101-104.

6th Generation Small Pressure Sensor

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ABSTRACT

A pressure sensor is a critical device for improving the precision and efficiency of engine management in order to reduce the environ-mental impact of cars. Fuji Electric has developed a 6th generation small-size digital trimming-type pressure sensor. High precision diaphragm processing is implemented using an anisotropic etching technique and the area of the sensor unit is reduced. Additionally, the design rules were revised, and as a result, the sizes of the circuitry and protective devices were reduced. Accordingly, the chip area was reduced by 70% while maintaining the equivalent functions, precision and EMC protection as conventional 5th generation products.

1. Introduction

The automobile industry is actively implementing environmental initiatives as regulations are strengthened in Europe, United States, Japan and Asia and elsewhere throughout the world. To comply with these stricter regulations, the industry is moving ahead with the development of hybrid electric vehicles (HEV), electric vehicles (EV) and the like. Meanwhile, for conventional gasoline vehicles and diesel vehicles, the air-to-fuel ratio is being controlled more finely to improve fuel economy and increase efficiency, and technical development to make exhaust gas cleaner is being accelerated.

A pressure sensor is one key device used to administer engine management to make engines run more efficiently and cleanly, and its importance has been increasing each year.

Fuji Electric has been mass-producing automotive pressure sensors since 1984. Since then, in response to changes of needs for reliability and detection accuracy pursuing strict environmental efficiency, Fuji Electric has proposed proprietary high-efficiency circuit technology and high-level MEMS (micro electro mechanical systems) technology so that these sensors are used in automobiles and motorcycles both in Japan and overseas. Since 2007, Fuji Electric has been mass-producing 5th generation digital trimming-type pressure sensors using a CMOS (complementary metal oxide semiconductor) process.

This paper introduces 6th generation small-size digital trimming type pressure sensors that have been realized in a smaller size while maintaining the functions, performance (detection accuracy), and EMC (electro magnetic compatibility) protection function of

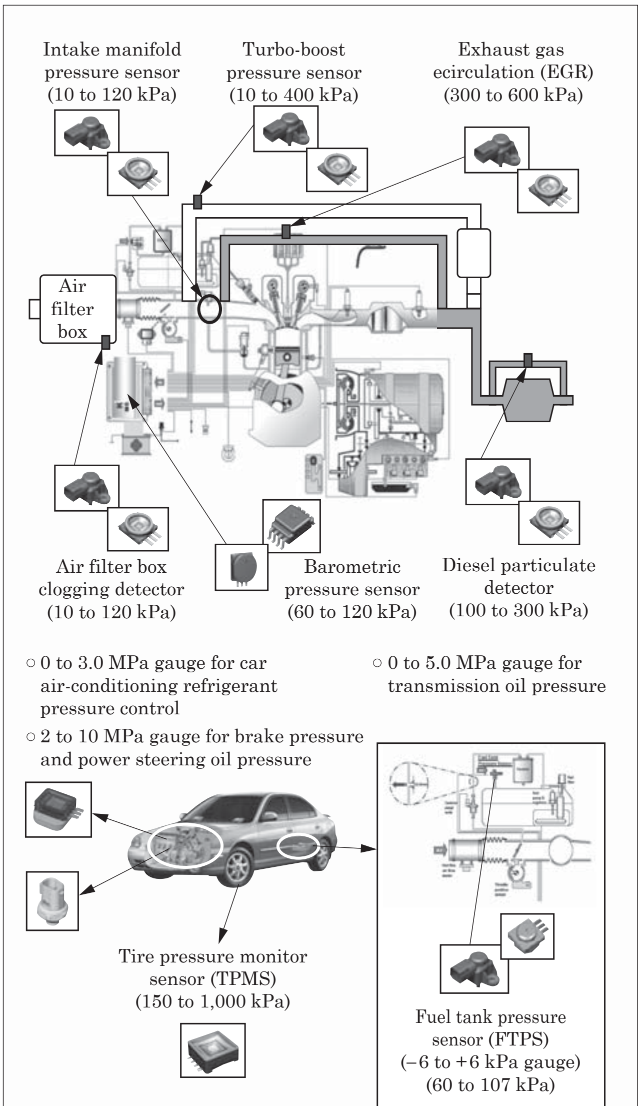

Fig.1 Applications of automotive pressure sensors

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the 5th generation digital trimming-type pressure sensors already being mass-produced.

2. Pressure Sensors for Automotive Applications

Fig. 1 shows applications of pressure sensors in automobiles. To improve the fuel economy of engines, electronic control of the fuel injection system has been promoted. In an electronic control fuel injection system, a MAP (manifold absolute pressure) sensor that measures the intake manifold pressure and a TMAP (temperature manifold absolute pressure) sensor equipped with a temperature sensing function are used. Such electronic control fuel injection systems are now being used often in motorcycles, and demands for even smaller size are intensifying. To improve fuel economy, pressure sensors are additionally used in many places, including an atmospheric pressure sensor used to perform advanced compensation so that fuel economy does not deteriorate when an automobile travels at a high elevation, a pressure sensor for detecting clogging of the air intake filter box, a pressure sensor for the turbo-boosting used in a turbo system that reuses exhaust gas, and a sensor for EGR (exhaust gas recirculation).

Furthermore, a pressure sensor for detecting clogging of a DPF (diesel particulate filter) is an example of a sensor used in response to the strengthening of exhaust gas regulations as typified by the Post New Long-term Regulation (2009) in Japan and Euro5 (2009) and Euro6 (2016) in Europe.

Pressure sensors applications for complying with safety regulations include a tank pressure sensor for detecting fuel leakage (FTPS: fuel tank pressure sensor) that is used in Europe, the United States and South Korea, and accompanying the establishment of the TREAD law (transportation recall enhancement accountability and document act) in the United States, a tire pressure monitoring system (TPMS) that monitors the tires for insufficient pressure.

In addition, there is increased demand for pressure sensors to control air-conditioning refrigerant and to control oil pressure of the transmission and elsewhere. Accordingly, the applications and demand for automotive pressure sensors are expanding rapidly.

3. Changes in Pressure Sensor Technology

Fig. 2 shows the technical progress of Fuji Electric's pressure sensors over time. In 1984, making full use of bipolar-integrated circuit technology and its surge tolerant capability, Fuji Electric commercialized a 1st generation of pressure sensors mainly for automotive engine control.

The subsequent 2nd and 3rd generations utilized single-chip integration techniques and thin-film resistor trimming (i.e., a method for laser-trimming thin-film resistors on a chip).

For the 4th generation, the world's first CMOS process-based single-chip digital trimming type automotive pressure sensor were mass produced.

The 5th generation, responding to market requests for smaller size and higher reliability, inherited the 4th generation's basic concept of an "All in one chip,"

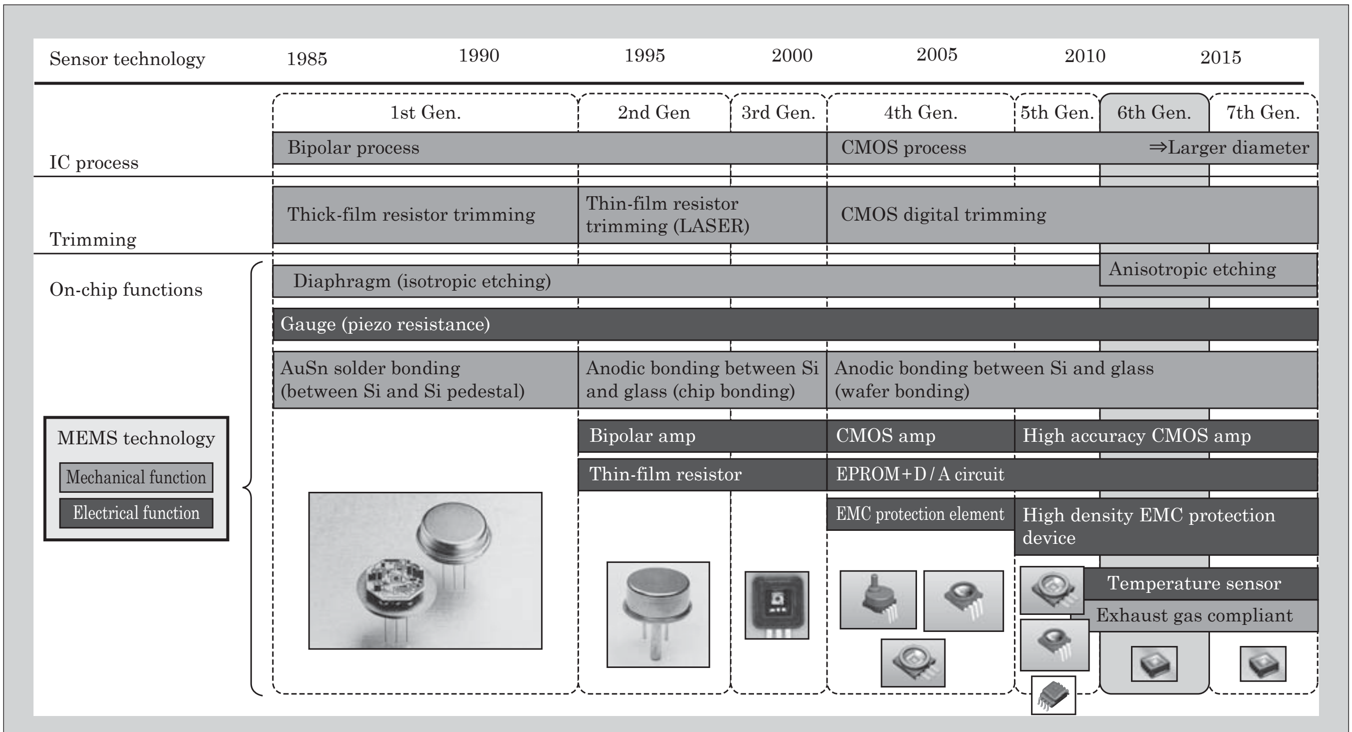

Fig.2 History of Fuji Electric's pressure sensor technology

and aimed to realize smaller size.

4. Characteristics of 6th generation small-size pressure sensors

Fig. 3 shows the appearance of a newly developed 6th generation small-size pressure sensor and a prior 5th generation pressure sensor.

The main feature of the 6th generation small-size pressure sensor is that the chip was fully optimized and that a limit design was carried out so as to maintain comparable functions and performance as the 5th generation pressure sensor but in a chip area that has been reduced to 70%.

Introduced below are three specific examples of the optimized designs incorporated into the 6th generation small-size pressure sensor: "diaphragm design," "integrated circuit design (digital/analog (D/A) converter)" and "protection device design."

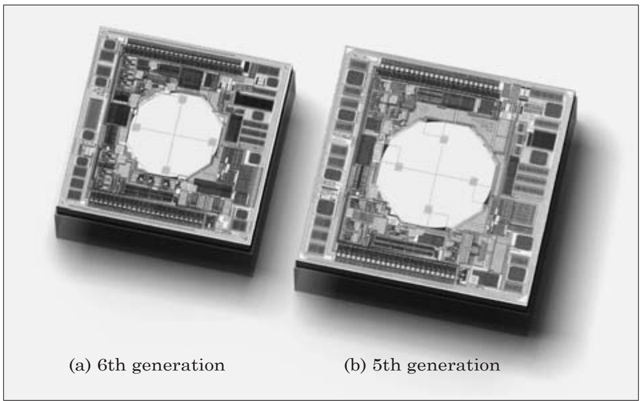

Fig.3 Appearance of pressure sensors

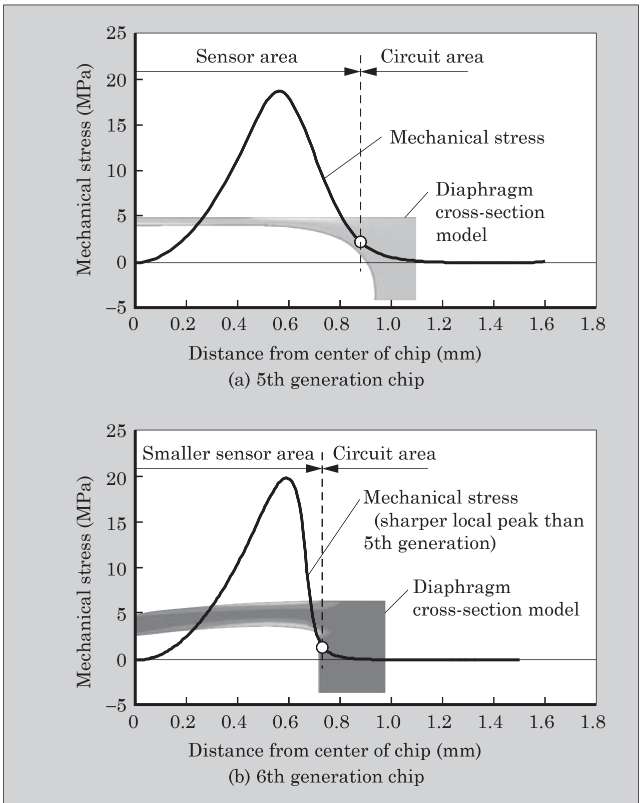

Fig.4 Example of diaphragm design based on FEM analysis

4.1 Diaphragm design

The diaphragm that forms the pressure sensor was optimized and designed using finite element method (FEM) analysis.

One example of the diaphragm design is shown in Fig. 4. Up until the 5th generation, pressure sensors had adopted an arch-shaped diaphragm as shown in Fig. 4(a). This shape was characterized as having a moderate distribution, without local concentrations, of mechanical stress (lines on the graph) when pressure was applied to the diaphragm. Thus, although an extremely rigid mechanical strength is obtained against applied pressure, the stress does have an effect, and there is an enlarged region in which analog circuits and devices other than the pressure sensor cannot be placed. That is, there were constraints on integration and miniaturization.

To remove these constraints, the 6th generation small-size pressure sensors adopted a diaphragm shape having a perpendicular cross-section that closely resembles Fig. 4(b), whereby the generated peak mechanical stress is sharper and more locally distributed. As a result, the mechanical stress that extends up to the circuit area side concentrates in the vicinity of the diaphragm unit, and there is an enlarged region in which devices can be placed on the circuit area side. Thus, by changing the cross-sectional shape, the diaphragm area could be reduced to approximately 60% of the size of the 5th generation while maintaining the same sensor sensitivity.

Fig. 5 shows a comparison of actual diaphragm cross-sectional shapes. 5th generation pressure sensors were manufactured using isotropic etching tech-

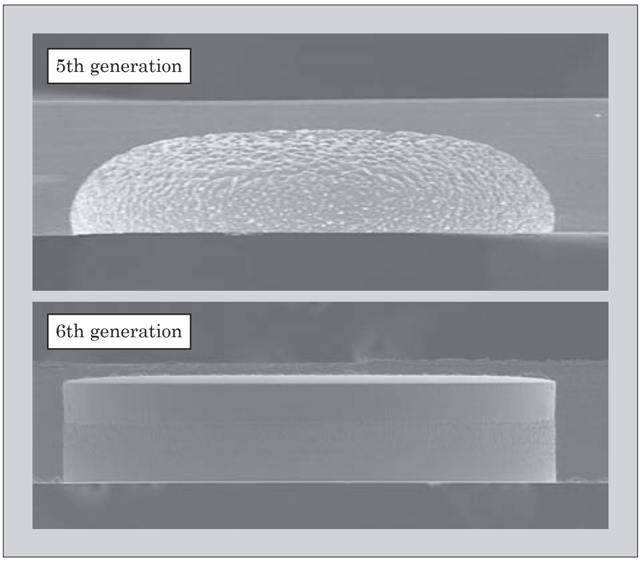

Fig.5 Comparison of diaphragm cross-sectional shapes

nology, but 6th generation small-size pressure sensors use anisotropic etching technology and achieve a cross-sectional shape that is nearly perpendicular. Through the application of Fuji Electric's proprietary process conditions, uniformity within ±2% of the in-plane depth of etching was achieved, and variation in the sensor detection sensitivity was reduced.

As an example of the sensor prototype results, Fig. 6 shows a graph of the nonlinearity. Nonlinearity indicates the amount by which the relationship between input (pressure) and output (voltage) deviates from a straight line, and a value closer to zero indicates greater linearity, i.e., a characteristic that is closer to the ideal.

In the 6th generation of small-size pressure sensors, in addition to changes in the cross-sectional shape, the diameter and thickness of the diaphragm, positioning of the sensing resistor, and the like were optimized. As a result, the 6th generation achieved an improvement from nonlinearity, compared to the 5th generation, over the entire range of diaphragm thicknesses as shown in Fig. 6.

4.2 Circuit design

Fig. 7 shows the circuit block diagram of a 6th generation small-size pressure sensor. This configuration has been inherited from the 4th generation, without eliminating any functions. In reducing the size of the circuit, based on experience gained in the 5th generation, criteria for the design of automotive pressure sensors was revised in order to realize higher integration with finer line widths.

Additionally, in the analog unit, especially for op-amps in the signal amplifier circuit, the sensitivity adjustment circuit, and the offset adjustment circuit, the device layout has been optimized without reducing the device size of MOS transistors and the like.

As a result, the circuit area could be reduced to approximately 80% that of the 5th generation. Furthermore, as shown in Table 1, the same functions, performance and trimming accuracy as the 5th generation could be maintained.

4.3 Protection device design

The protection devices in 6th generation small-size pressure sensors have also been subjected to a thorough review of their design criteria, and have been miniaturized. The device area has been reduced to approximately 80% of the size of 5th generation devices, while realizing the equivalent surge protection and noise protection. Specific performance characteristics are listed in Table 1. For example, by ensuring at a tolerance of least ±600 V in the case of a machine model (0 Ω/ 200 pF) ESD (electrostatic discharge) test, and so on, the highest level of surge protection and noise protection for automotive applications is realized with a single chip.

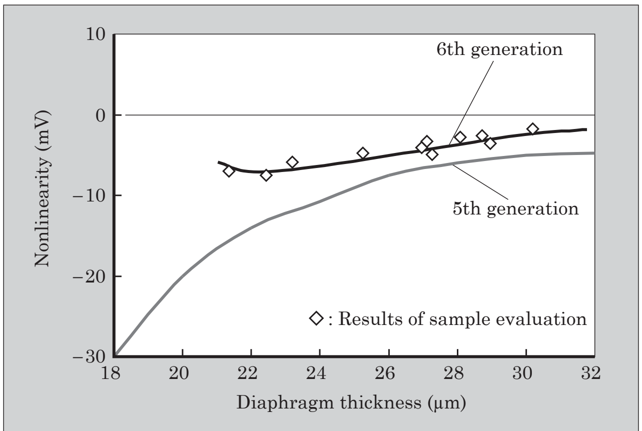

Fig.6 Nonlinearity of sensor output

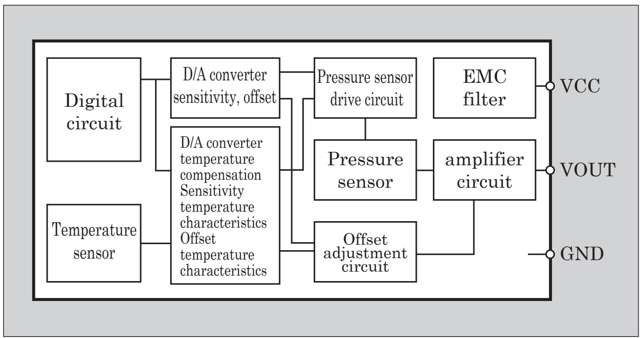

Fig.7 Circuit block diagram of 6th generation small-size pressure sensor

Table 1 Comparison of main performance characteristics of pressure sensors

Item		6th generation	5th generation
Chip size (area ratio)		70%	100%
Diaphragm size (area ratio)		60%	100%
Pressure range		60〜500 kPa	
Absolute max. pressure		Pressure range×3	
Supply voltage		5±0.25 V	
Output range (when supply voltage is 5 V)		0.5 to 4.5 V	
Output error (at 25 °C/125 °C)		1%FS/1.5%FS	
Nonlinearity (diaphragm thickness of 30 μm, 255 °C)		−2.5 mV (typ)	−5 mV (typ)
Sink/Source current		Sink 1 mA Source 0.1 mA	
ESD (external interface pin)			
	MM (0 Ω, 200 pF)	±1 kV or greater	
	HBM (1.5 Ω, 100 pF)	±8 kV or greater	
ISO 7637 (Pulse1, 2, 3a, 3b)		Clears LEVEL-IV	
Impulse		±1 kV or greater	
Latch-up (current injection method)		±500 mA or greater	
EMS (G-TEM) (100 V/m)		Fluctuation: 1%FS or less	
Over voltage protection (between VCC-GND)		16.5 V (max)	
Reverse connection (between VCC-GND)		0.3 A (max)	

5. Postscript

This paper has presented an overview and described the characteristics of 6th generation small-size pressure sensors. With "global warming" being the keyword, stringent requirements for improved environmental performance and product performance are expected to continue to accelerate as products are deployed widely throughout Japan and overseas. Fuji Electric intends to continue to respond to market needs and to develop products deemed essential by the market.

Supplemental Explanation

Three-level inverter technology

Multilevel inverters typified by three-level inverters have a variety of advantages over general two-level inverters. For example, the voltage waveform at the converter output of a two-level inverter is a pulse width modulation (PWM) generating pulses of $\pm E_d$ from the central zero point, whereas that of a three-level inverter is a PWM generating pulses of $\pm E_d/2$ and $\pm E_d$ from the central zero point, as shown in Fig. 1.

As a consequence, the waveform of a three-level inverter is closer to a sinusoidal wave, so that an LC filter for making output waveforms sinusoidal can be rendered compact. What is more, the magnitude of the voltage fluctuation of a three-level inverter per switch operation is half that of a two-level inverter. This brings about an almost 50% reduction in the switching loss of the switching element and a reduction in noise generated by the device. Using a three-level inverter characterized by these features is an effective approach to making systems more compact and more efficient.

Of the many types of three-level inverters, those connected to the neutral point (N) of the direct-current power supply shown in Fig. 1 are called neutral-point-clamped (NPC) inverters. They are called this because the voltage applied to the switching element is kept clamped to a voltage that is half the direct-current voltage E_d.

As opposed to NPC inverters, advanced-NPC (A-NPC) inverters have seldom been put to practical use to date, although they have the advantages of reduced current loss because they have simplified circuits and a small number of current pass elements. This is because the circuit connected to the neutral point requires a bidirectional switching element. Trying to achieve this configuration with a general insulated gate bipolar transistor (IGBT) and diode results in there being two current pass elements for the current passing through the circuit connected to the neutral point. This means that there is not much difference in continuity loss between NPC inverters and A-NPC inverters. In addition, there are some problems with the wiring method and the snubber circuit, such as a high surge voltage resulting from the effect of wiring inductance during switching.

We have successfully resolved the aforementioned problems by applying a reverse-blocking IGBT (RB-IGBT), which is Fuji Electric's original technology, to circuits connected to the neutral point and developing a module designed exclusively for A-NPC inverters. We have thereby made it possible to make practical use of A-NPC inverters.

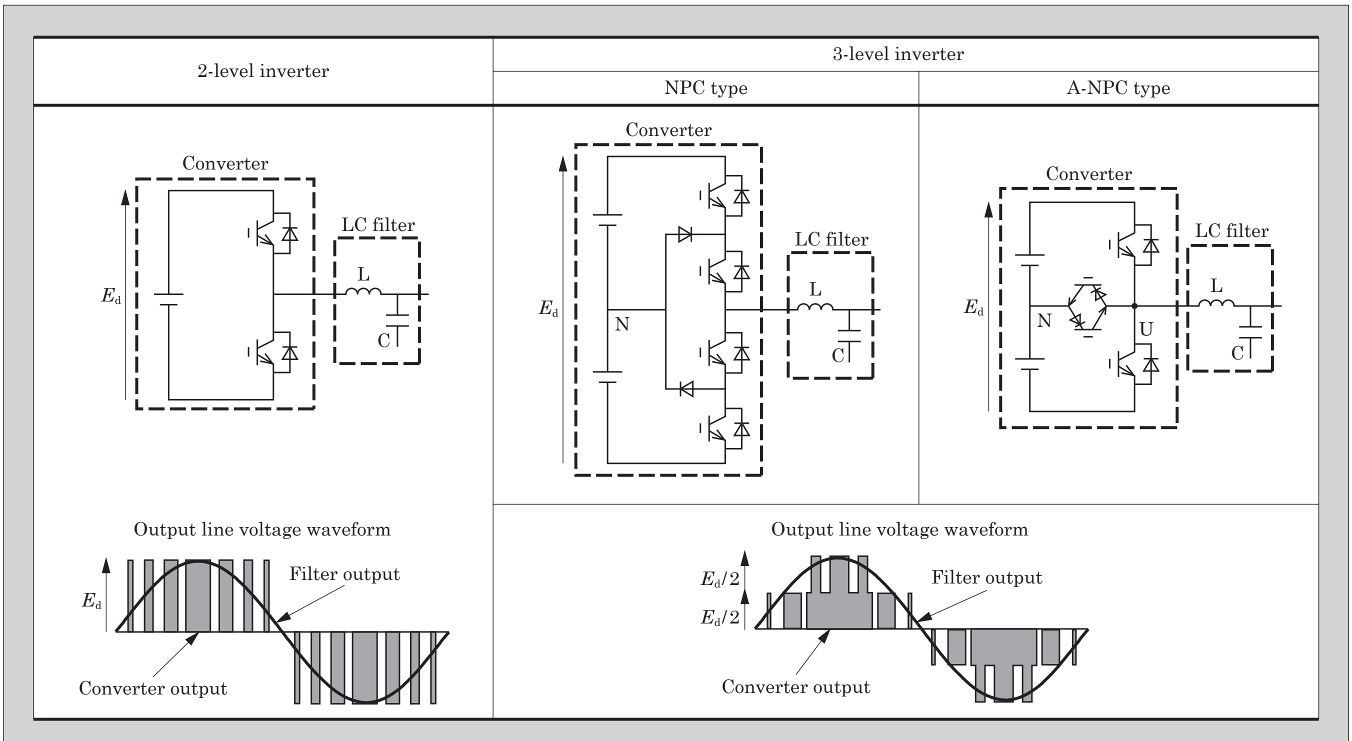

Fig.1 Comparison of voltage waveform between two-level inverter and three-level inverter circuits

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