Recent Technical Trends and Future Prospects of IGBTs and Power MOSFETs

Tsuneo Ogura
Discrete Semiconductor Division, Semiconductor & Storage Products Company,
Toshiba Corporation
Kawasaki city, Japan

Abstract— **In this paper, recent technical trends and future prospects of IGBTs and power MOSFETs is presented. Device technologies mainly for reducing power loss are discussed. This is because the reduction in power loss of these power devices is important for home and consumer appliances. Firstly, historical main road maps of these device technologies are introduced. Next, proposed future road maps and distinguishing results are also introduced. And, a comparison with IGBTs, power MOSFETs and SiC-MOSFETs is discussed. Finally, I will conclude that Si-power devices and SiC-power devices will coexist in home and consumer appliances by taking advantage of each characteristic in the near future.**

Keywords— power semiconductor device, IGBT, power MOSFET

I. INTRODUCTION

In recent years, wide-band-gap (WBG) power semiconductor devices, such as SiC and GaN power devices, are expected as next-generation power devices from the requirement of energy-saving in home and consumer appliances. This is because these WBG power devices have a great potential as compared to Si power devices that are widely used today. This potential includes the characteristics of low on-state loss, high switching speed and high temperature operation, resulting from the advantage in the physical properties over Si materials. There is also the background that the improvements of Si power semiconductor devices, promoted over more than 30 years, have close to their limit that is determined by the physical properties of Si materials. Therefore, Si power devices are believed to have a few rooms of performance improvement.

However, Si power devices, such as IGBTs and power MOSFETs are now progressing steadily with these characteristics. And it is considered that these devices play an important role in home and consumer appliances in the near future. So, in this paper I will discuss outlook and recent technical trends and future prospects of IGBTs and power MOSFETs, and will compare with WBG power devices.

A general correlation of main characteristics of power devices and main characteristics required from home and consumer appliances are the same both in Si power devices and WBG power devices (Fig. 1). Low power-loss, high temperature operation and high ruggedness in power devices are required to achieve compact & light weight, low noise, low cost, high reliability and high efficiency for home and consumer appliances. Among them, it is particularly important to realize low power-loss in power devices without sacrificing the other properties.

In addition, discussions in this paper are not limited to home and consumer appliances, because the discussions may be considered as common technologies in other appliances, such as general purpose, automotive, electric train, information and communication.

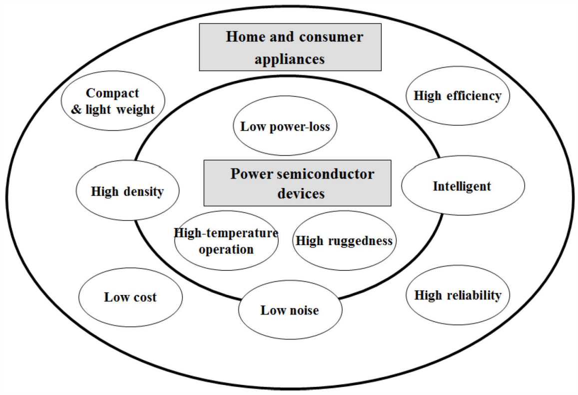

Fig.1 General correlation of characteristics of power devices and characteristics required from home and consumer appliances.

II. TECHNICAL TREND OF IGBTS

First, I will introduce main application products of home and consumer appliances of IGBTs (Fig. 2). IGBTs are widely used in these products, such as air conditioners, refrigerators, washing machines, photovoltaic power conditioners, digital cameras, microwave ovens, induction heaters and rice cookers. Many types of circuit configurations, such as inverter, voltage resonant, current resonance and pulse-current generator circuits, are used for these appliances. In this regard, the circuits for home and consumer appliances are vivid contrast to those for industrial and automotive appliances which have mainly inverter circuits for driving motors. Therefore, a performance required to IGBTs for home and consumer appliances, is different at each appliances in detail design level. However, low power-loss as a basic characteristic is always required for these circuits. Therefore, though it is not limited to home and consumer appliances, I will describe trend toward to lower loss of IGBTs in this section.

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Fig.2 Application examples of IGBTs for home and consumer appliances.

To realize low power-loss in bipolar devices such as IGBTs, it is basically important to improve the trade-off relation between the reduction of on-state voltage by increasing accumulated carriers and the reduction of turn-off switching loss by high-speed discharge of accumulated carriers. Therefore, in the beginning of development stage, the reduction of turn-off switching loss by high-speed discharge of accumulated carriers was an important development challenge. In this view point, the injection efficiency control of a p-collector layer and the reduction of carrier lifetime in an n-base layer were most important issues. In the next step of development stage, the reduction of on-state voltage was a major problem, because the basic structure of IGBTs hardly accumulates carriers in the n-base layer near a p-base layer. Therefore, a structure with electron injection enhancement effect (IE-effect) has been developed [1], and a significant reduction in on-state voltage was realized (Fig. 3).

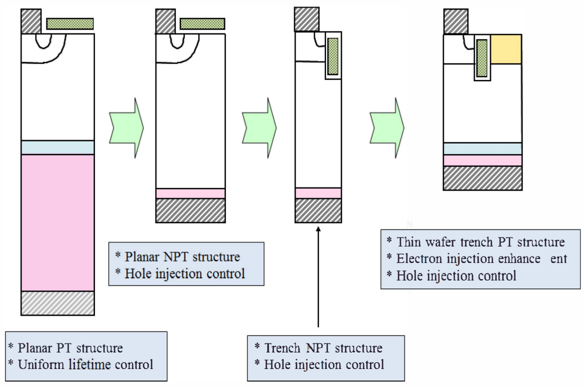
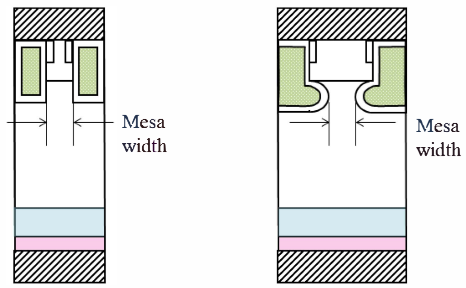


Fig. 3 Historical progress in device structures of IGBTs.

Latest trend to realize low on-state voltage, a narrow mesa structure for further increase in electrons at an emitter side was proposed as shown in Fig. 4(a). It was theoretically shown that a minimum value of on-state voltage of IGBTs is realized at a case of integration of the both sides of channel of the trench surface [2]. To realize this condition, the mesa width of two trench gates located next to each other was calculated to about 20 ~ 40 nm. And, on-state voltage at 600 V IGBTs was expected to reduce to 2 mΩcm^2 which is about 30 % reduction compared to the latest IGBTs. Also, at this condition, it was expected that turn-off switching was also faster than that of the latest IGBTs, because only electron current contributes to conduction by suppressing injection amount of holes from the p-collector.

A reduction in on-state voltage by the narrow mesa width has been experimentally verified [3]. A 40 % reduction of the mesa width has realized 80 % of on-state voltage compared to that of the latest IGBTs. However, it is considered that the effect of narrow mesa structure is not proportional to a reduction rate in on-state voltage, but is gradually saturated. And ultimately, a minimum value of on-state voltage will lead to the assumption of the theoretical analysis described above.

Furthermore, since a layout of gate electrode and emitter electrode at the surface of emitter is difficult at the condition of fine mesa width, a fine pitch structure only at the trench bottom (partially narrow mesa structure) is also reported [4]. Figure 4(b) shows a schematic diagram of an ultra-fine pitch IGBT having a minimum width of 30 nm mesa. By fining the mesa width, because carrier density at the emitter side is increased, on-state voltage is reduced theoretically and experimentally. However, it is noted that due to carrier density increase at the emitter side, delay time at turn-off switching is increased and resulting switching loss increase.



(a) Narrow mesa structure (b) Partially narrow mesa structure

Fig.4 Recent progress in device structures of IGBTs.

In order to miniaturization of the mesa width, it is considered that an adoption of the process developed for the LSI is a powerful tool. It has been reported that on-state voltage can be reduced by reducing a structure design pitch in accordance with a certain rule likely to LSI process miniaturization rule [5]. However, a special structure design is required for IGBTs, such as a trench gate structure, an oxide film thickness and a collector layer profile. Therefore, it should be pointed out that a proper modification of the LSI process is an important issue for next generation IGBTs.

As described above, an introduction of fine pitch process technology is important for next generation of IGBTs. Possibility of reduction in on-state voltage is shown by the fine pitch IGBT, and development has been in progress. However, it is considered that there are many problems to be solved, such as processing technology, reliability of oxide film, increase in switching loss due to carrier accumulation and ruggedness. Therefore, the reduction in on-state voltage should be developed in parallel without sacrifice of these characteristics.

Next, I will discuss a latest trend for reverse conductive type IGBTs (RC-IGBTs), which have already been developed for home and consumer appliances. Because the reduction in on-state voltage is progress as described above, a downsizing of chip area has been achieved by increasing current density to realize both size and cost reductions. However, a significant reduction in chip size becomes difficult in recent years. Therefore, to realize the reduction in chip area, a new approach of functional integration has been studied. Power ICs with integrated control circuit are those examples, but I will introduce RC-IGBTs which aim to integrate power devices. Power electronics circuits for home and consumer appliances, an inverse parallel connection of IGBT and wheeling diode (FWD) is commonly used. IGBTs do not integrate FWDs in their original device structure, unlike MOSFETs. Therefore, a special structure of adding an n-cathode layer for FWDs has been developed as shown in Fig.5. This special integrated structure can reduce chip area compared with the conventional two-chip configuration of IGBTs and FWDs.

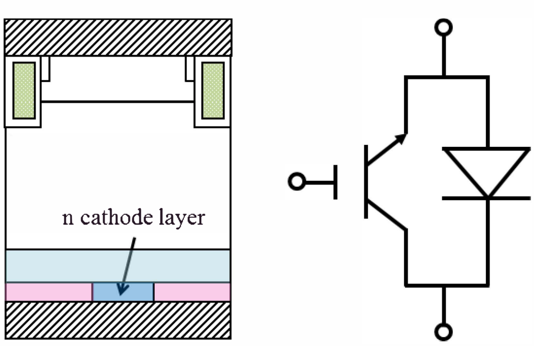


Fig.5 Structure cross section of reverse conducting IGBT and its equivalent circuit.

RC-IGBTs are already applied to soft switching circuits. Figure 6 shows switching waveforms of IGBTs in a current resonance circuit and a voltage resonance circuit to achieve soft switching. The former is used for microwave ovens; the latter is used for IH cooking heaters, and so on. Because high-frequency switching is essentially required for these applications, these soft switching circuits to reduce in switching loss are used. In these resonant circuits, high-frequency operation of more than 20 kHz has been realized. In addition to this, it is a merit to form a resonant circuit without using an additional circuit with a large inductance. For these circuits, a device design of RC-IGBTs is easier than that for the hard switching circuit, because over load condition at switching transient is light and the current flowing through FWDs is small. Therefore, RC-IGBTs for the soft switching circuit have developed ahead of that for the hard switching circuit.

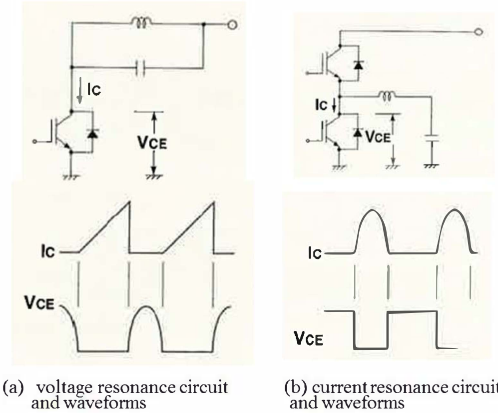


Fig.6 Circuits and switching waveforms of reverse conducting IGBTs in current resonance circuit and voltage resonance circuit.

Thereafter, RC-IGBTs for the conventional hard switching are also developed. It was reported that, as a loss reduction in a 600 V RC-IGBT, increase in rated current of about 33 % to 150 % has been realized at three types of packages. Miniaturization of these packages has achieved with downsizing by integrated chips [6].

For an RC-IGBT, because an IGBT and a FWD are integrated in one chip, a device and package design that takes into account both influence of heat and electrical effects is important. It is believed that there still remain many problems to be solved for wide range of applications; RC-IGBTs shall continue to contribute significantly to realize small size and high density of power electronics systems.

TECHNICAL TREND OF POWER MOSFETS

First, I will introduce main application products of home and consumer appliances of power MOSFETs (Fig.7). Power MOSFETs are widely used in these products, such as LCD-TVs, air conditioners, photovoltaic power conditioners, LED lightings, printers and power tools. Many types of circuit configurations, such as AC/DC converters, PFC (Power Factor Correction) circuits, DC/DC converters and DC/AC converters, are used for these applications. Like IGBT case, low power-loss as basic characteristics is always required for these circuits. Therefore, though it is not limited to home and consumer appliances, I will mainly describe trend toward to lower loss of power MOSFETs in this section.

Power MOSFETs are switching elements which are most widely used in breakdown voltage range from 10 V to around 600 V. Here, devices having breakdown voltage from approximately 20 V to 30 V are called low-voltage MOSFETs (LV-MOSFETs). And LV-MOSFETs are used widely in DC/DC converter circuits to obtain a DC voltage required in power circuits of home and consumer appliances. The device of this voltage region, on-resistance is determined mainly by channel resistance rather than n-type drain layer resistance, because of narrow and high concentration of n-type drain layer. For this reason, reduction of channel resistance is an important issue. Also, reduction of gate capacitance for high-speed switching is an important issue. Therefore, fine patterning and etching process developed for the LSI fabrication process have been applied to realize low channel resistance and low gate capacitance.

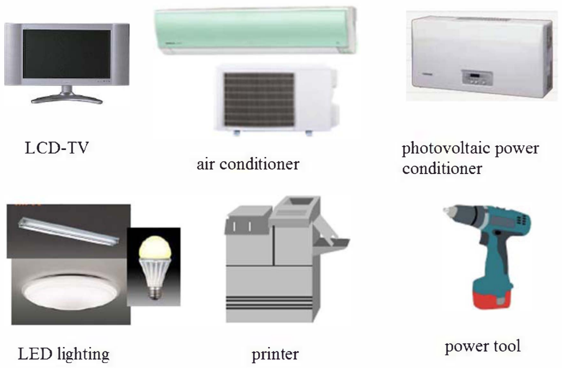


Fig.7 Application examples of power MOSFETs for home and consumer appliances.

At initial stage, planar gate structures were developed. But now trench gate structures have become a mainstream, because channel density is easily increased by fining of trench pitch (Fig. 8). Features, compared to IGBTs with trench structure, are advanced fine trench pitch because of shallow trench depth and thin oxide. Further, in power MOSFETs, because feedback capacitance is dominant over switching unlike IGBTs, special device structure with trench structure is important.

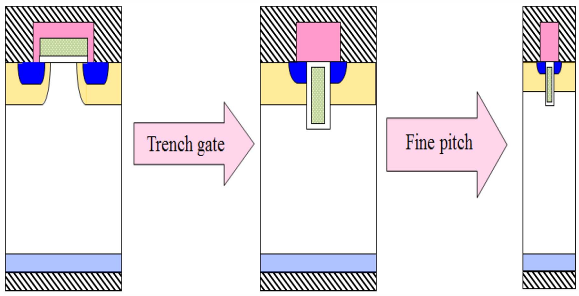


Fig. 8 Historical progress in device structures of low-voltage MOSFETs.

Latest two types of trench gate structure for LV-MOSFETs are showed in Fig. 9. Figure 9(a) shows a LV-MOSFET with the breakdown voltage of 35 V which has reduced feedback capacitance by increasing the thickness of the oxide film in the trench bottom [7]. A 27% reduction from 762 pF to 207 pF at drain voltage of 0 V and a 55 % reduction from 163 pF to 89 pF at drain voltage of 30 V have been realized when compared with the conventional structure. As the result, conversion efficiency of 1.5 % higher than that of the conventional structure in switching operation of 300 kHz in a DC/DC converter circuit from 20 V to 1.5 V was realized. Figure 9(b) shows a LV-MOSFET with the breakdown voltage of 25 V which has a buried source electrode in the bottom of trench [8]. A feedback capacitance can be reduced to 85 % as compared with the conventional structure without buried source electrode, thereby achieving a higher switching characteristic of two times or more.

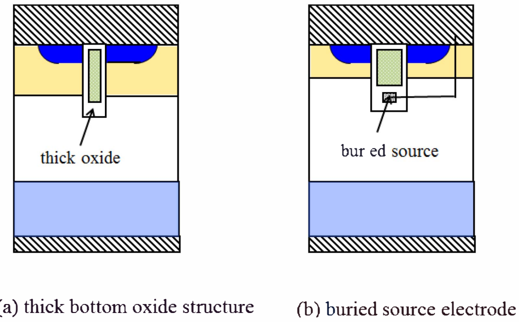


Fig.9 Recent progress in device structure of LV-MOSFETs.

In addition, to improve the trade-off relation between switching speed and on-resistance, a combination structure of trench and planar structure has also been developed in recent years (Fig. 10). This planar channel structure can reduce feedback capacitance drastically. Also this planar structure can be fabricated using fully LSI fine patterning process, so it has an advantage on the performance improvement by miniaturization. And the trench structure is used to form drain electrode at the bottom of the chip which can realize high heat dissipation by double-sided cooling [9].

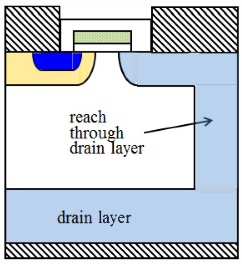


Fig.10 Structural cross section of new planar MOSFET.

Next, power MOSFETs having breakdown voltage from 500 V to 600 V are called high-voltage MOSFETs (HV-MOSFETs). And HV-MOSFETs are used widely in the primary side of AC/DC converters to obtain from AC power supply to DC voltage which is usually required for home and consumer appliances. Because this type of converters always operates, improvement of conversion efficiency by reducing on-resistance of HV-MOSFETs is very important for energy conservation.

In the device of this voltage range, because of low-concentration and wide n-type drain layer, on-state resistance is mainly determined by n-type drain layer resistance rather than channel resistance. Therefore, instead of the fine pitch of gate structure, a design of the n-type drain layer is important. However, on-resistance at conventional planar MOSFETs has approached a theoretical limit (about 70 mΩcm^2 in 600 V class MOSFETs) by the latter half in the 1990’s.

At that stage, Super-Junction MOSFETs (SJ-MOSFETs) have been developed as shown in Fig. 11. To realize the SJ-MOSFET structure, it is necessary to form a p/n-pillar layer in the horizontal direction. By adopting this pillar structure, it is possible to increase the concentration of the n-drain layer. Moreover, it is possible to reduce on-state resistance by decreasing the pitch of the p/n-pillar layer (Fig. 12). Therefore, a technique for a narrow p/n-pitch width is a major issue, and the development of process technology is a key point. The basic and original method for forming p/n-pillar layer is repeating epitaxial growth and implantation method (so-called multi-epitaxial method). Using this method, it is believed that control of the epitaxial layer thickness and control of the concentration of the p/n-pillar layer is easy, but it is necessary to increase the number of epitaxial growth steps to obtain a narrow pitch of the p/n-pillar layer. Therefore, there is a limit from the viewpoint of production cost. And, various process techniques have been studied to solve this problem.

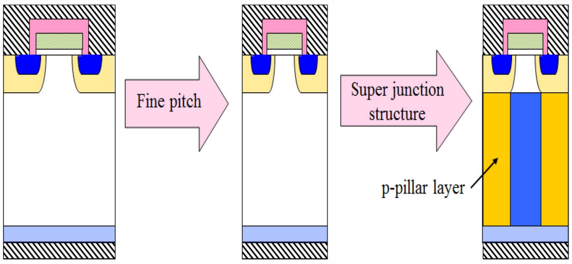


Fig. 11 Progress in device structures of high-voltage MOSFETs.

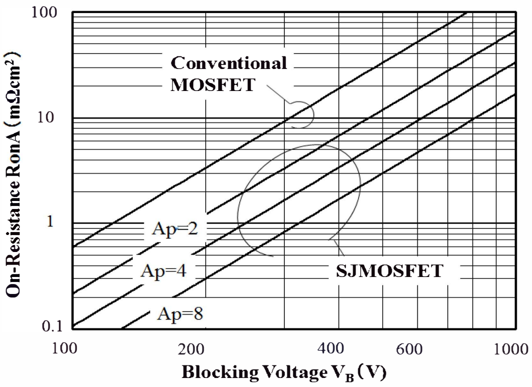


Fig.12 Ideal On-Resistance of DMOSFETs and SJMOSFETs as a parameter of pillar aspect ratio (Ap).

Recently, a method of forming the p/n-pillar layer using deep trench filled by epitaxial growth for the p-pillar layer has been developed. Because of simplification of process, this method (so-called single-epitaxial method) is expected to be a next generation process for SJ-MOSFETs. To obtain good performance by using this method, it is important to form a uniform epitaxial p-pillar layer in the trench without crystal defects. Recently, epitaxial p-pillar layer of 37 μm depth in the trench has been formed, and on-resistance has been reduced to about 1/10 of a conventional MOSFET. This SJ-MOSFET has the on-resistance of 7.8 mΩcm^2 at the breakdown voltage of 600 V class [10].

Figure 13 shows a road map of on-resistance reduction in SJ-MOSFETs. The on-resistance of current production level is about 20 mΩcm^2, but that of research level is 7.8 mΩcm^2. However, the progress of on-resistance reduction has not progressed from 2008. It is considered that difficulty in process has remarkably increased, but development of new technology is desired in the future.

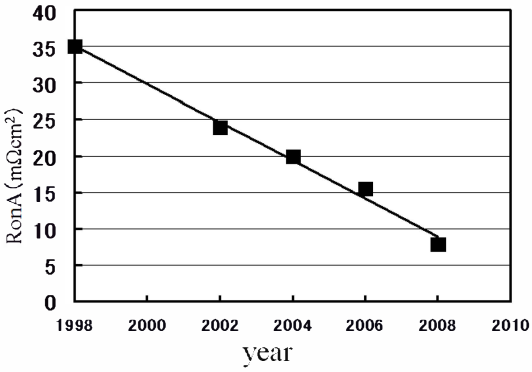


Fig. 13 Roadmap for deduction in on-resistance of SJ-MOSFETs at research level.

In addition to this, reduction of the switching noise has become important for high-switching speeding condition. Increase in dv/dt due to fast switching causes noise. A new structure which can reduce noise even at high dv/dt condition is shown in Fig.14 [11]. A dummy p-base layer can control internal parasitic capacitances of the MOSFET. Therefore, it is possible to use in high dv/dt condition, realizing high switching speed without sacrificing noise problem.

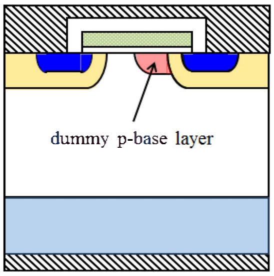


Fig.14 Structural cross section of new HV-MOSFET.

III. CONCLUTIONS

Finally, I will compare on-state voltage between IGBTs, power MOSFETs and SiC-MOSFETs at the breakdown voltage of 600 V which is commonly used in home and consumer appliances. The relationship between on-state voltage and chip size is shown in Fig. 15. In IGBTs, the internal 0.7 V potential due to the pn-junction were added to the on-resistance. In addition, the relation for MOSFETs, SJ-MOSFETs and SiC-MOSFETs can be expressed only by changing parameter of on-resistance. The on-resistance of latest SJ-MOSFET was considered as 20 mΩcm^2, and the limit value of the on-resistance was estimated as 5 mΩcm^2. In SiC-MOSFETs, on-resistance of 2 mΩcm^2 of current production situation is plotted and almost theoretical limit value of on-resistance of 0.2 mΩcm^2 is also plotted in the figure.

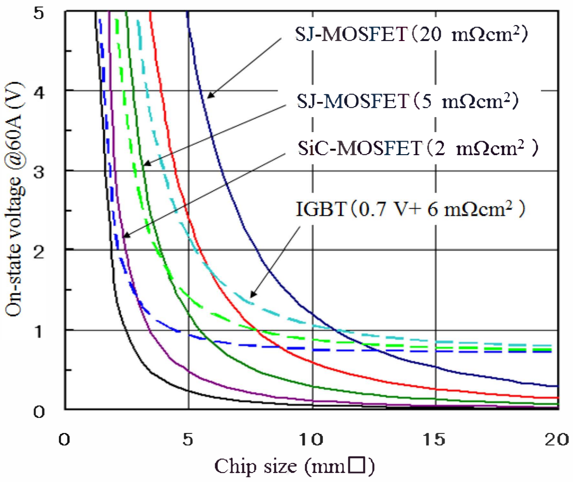


Fig.15 Relationship between on-state voltage and chip size with IGBTs and power MOSFETs.

When comparing the on-state voltage of 60 A at the chip size of 5 mm□, the on-state voltage of a latest IGBT is about 2 V, that of a latest SJ-MOSFET is about 5 V and that of a latest SiC-MOSFET is about 0.5 V. Ignoring switching losses assumed low switching frequency driving, the turn of low loss is SiC-MOSFET, IGBT and SJ-MOSFET. However, because of high cost of SiC-MOSFETs, the chip size of SiC-MOSFETs should be reduced. Assuming that chip size of SiC-MOSFETs is 1/4 compared with that of IGBTs, it is considered that SiC-MOSFETs do not have many advantages compared with IGBTs.

However, SiC-MOSFETs have a merit of lower switching loss than IGBTs. Therefore, it is necessary to apply SiC-MOSFETs to suitable systems by comprehensively considering their characteristics. The problem is that the on-resistance of current situation has stopped at 10 times larger than that of theoretical limit of SiC-MOSFETs. If this theoretical limit is achieved, the on-resistance of the 60 A will be significantly decreased to about 0.05 V at the chip size of 5 mm□ and about 0.2 V at the chip size of 1/4.

Difficulty degree of process technology to develop next generation IGBTs and power MOSFETs for home and consumer appliance is increasing; however, technologies for total loss reduction in these devices will progress in the future. In the near future, it is believed that Si-power devices and SiC-power devices will coexist in home and consumer appliances by taking advantage of each characteristic.

In recent years, the growth of power consumption by industrial usage has stopped in Japan, but that for home and consumer appliances has extended year by year. It considered that this is caused by the growth of numbers of air-conditioners and lightings and high functionality of refrigerators and TV sets. Also, I believe that the use of energy storage at home, including solar power, will rapidly increase in the future. For these reasons, energy efficiency at home and consumer appliances has become an increasingly important issue. Therefore further development towards power electronics with higher energy efficiency and power devises with lower total loss are strongly expected.

REFERENCES

[1] M.Kitagawa, I.Omura, S.Hasegawa, T.Inoue and A.Nakagawa, “A 4500 V Injection Enhanced Insulated Gate Bipolar Transistor (IEGT) Operating in a Mode Similar to a Thyristor”, IEDM’93, pp.679-682.

[2] A.Nakagawa, “Theoretical Investigation of Silicon Limit Characteristics of IGBT”, ISPSD’06, pp.5-8, 2006.G. Eason, B. Noble, and I. N. Sneddon, “On certain integrals of Lipschitz-Hankel type involving products of Bessel functions,” *IEEE Trans. on Power Electronics*, vol. 247, no. 8, pp. 529-551, 1995.

[3] S.Honda, Y.Haraguchi, A.Narazaki, T.Terashima and Y.Terasaki, “Next Generation 600V CSTBTTM with an Advanced Fine Pattern and a Thin Wafer Process Technologies”, ISPSD’12, pp.149-152, 2012.

[4] M.Sumitomo, J.Asai, H.Sakane, K.Arakawa. Y.Higuchi and M.Matsui, “Low loss IGBT with Partially Narrow Mesa Structure (PNM-IGBT)”, ISPSD’12, pp.17-20, 2012.

[5] M.Tanaka and I. Omura, “Scaling Rule for Very Shallow Trench IGBT toward CMOS Process Compatibility”, ISPSD’12, pp.177-180, 2012.

[6] H.Ruthing, F.Hille, F.-J.Niedernostheide, H.J.Schulze and B.Brynner, “600 V Reverse Conducting (RC-) IGBT for Drives Applications in Ultra-Thin Wafer Technology”, ISPSD’07, pp.27-30, 2007.

[7] M.Darwish, C.Yue, K.H.Lui, F.Giles, B.Chan, K.Chen, D.Pattanayak, Q.Chen, K.Terrill and K.Owyang, “A New Power W-Gated Trench MOSFET (WMOSFET) with High Switching Performanc”, ISPSD’03, pp.24-27, 2003.

[8] P.Goarin, G.E.J.Koops, R.v. Dalen, C.L.Cam and J.Saby, “Split-gate Resurf Stepped Oxide (RSO) MOSFETs for 25V applications with record low gate-to-drain charge”, ISPSD’07, pp.61-64, 2007.

[9] G.Loechelt, G.Grivna, L.Golonka, C.Hoggatt, H.Massie, F.D.Pestel, N.Martens, S.Mouhoubi, J.Roig, T.Colpaert, P.Coppens, F.Bauwens and E.D.Backer, “A High-Speed Silicon FET for Efficient DC-DC Power Conversion”, ISPSD’12, pp.85-88, 2012.

[10] J.Sakakibara, Y.Noda, T.Shibata, S.Nogami, T.Yamaoka and H.Yamaguchi, “600V-class Super Junction MOSFET with High Aspect Ratio P/N Columns Structure”, ISPSD’08, pp.299-302, 2008.

[11] W.Saito, S.Aida, S.Koduki amd M.Izumisawa, “Improvement of Switching Trade-off Characteristics between Noise and Loss in High Voltage MOSFETs”, ISPSD’11, pp.316-319, 2011.