SiC-MOSFET with High Threshold Voltage and Low On-Resistance Using Halo Structure

KOBAYASHI, Yusuke* OHSE, Naoyuki ‡ KOJIMA, Takahito ‡

ABSTRACT

Fuji Electric has developed a trench gate MOSFET that uses silicon carbide (SiC) to reduce power dissipation of power semiconductor devices. Although shortening the MOSFET channel length can further reduce power dissipation, this makes it necessary to suppress the drop in the threshold voltage and breakdown voltage due to the short-channel effect. The simulations and prototype for a vertical trench gate SiC-MOSFET with a halo structure demonstrated the suppression of the short-channel effect. We were thereby able to reduce on-resistance while maintaining a high threshold voltage and breakdown voltage.

1. Introduction

Increasing demand for energy-saving products to realize a low-carbon society has led to the need to use energy-saving power semiconductor devices which are used in power electronics devices. Under these circumstances, it was discovered that vertical metal-oxide-semiconductor field-effect transistors (MOSFETs) using silicon carbide (SiC) offered reduced power loss over conventional vertical insulated gate bipolar transistors (IGBTs) using silicon (Si), making them a potentially ideal candidate for power semiconductor devices. Fuji Electric has already produced a prototype of a vertical SiC-MOSFET equipped compact, lightweight power conditioner (PCS[1]) and begun commercializing[2] PCS products for mega solar applications in its efforts to promote the development of energy-saving power electronics devices. However, even greater power loss reductions than those offered by SiC-MOSFET are necessary to deliver further energy savings, and reducing on-resistance $R_{on}{\cdot}A$ during conduction, the dominant of loss factors, is key to achieving this. This paper describes a vertical SiC-MOSFET which simultaneously achieves low on-resistance and suppresses short-channel effects using a halo structure.

2. MOSFET Low On-Resistance and Short-Channel Effects

Fuji Electric has achieved[3],[4] the world's highest level of low on-resistance through the adoption of trench gate structure (see Fig. 1) high channel density and high channel mobility. Furthermore, we have simultaneously reduced the electrical field applied to the gate oxide film with buried p-layers and realized high

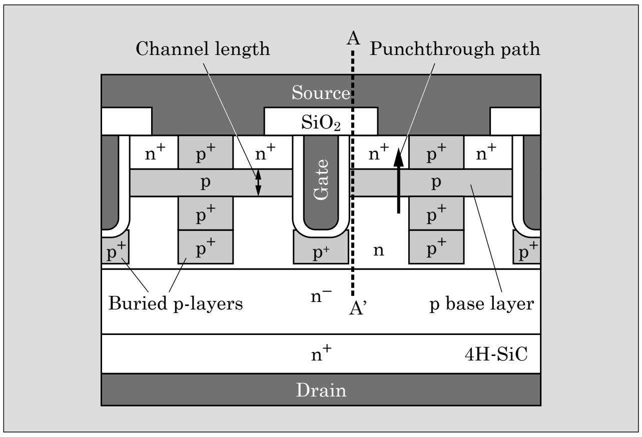

Fig.1 Cross-sectional structure of trench gate MOSFET

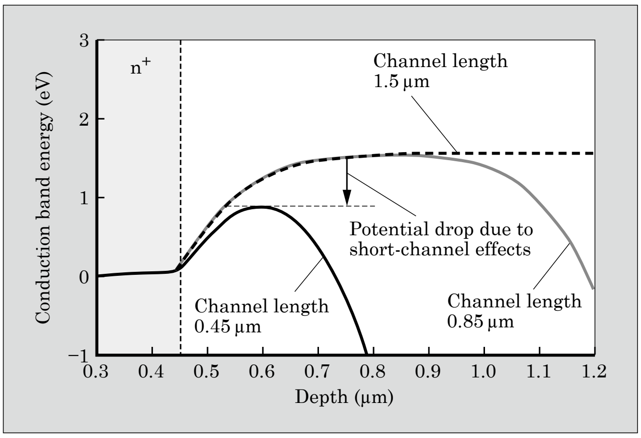

Fig.2 Channel length dependency of channel section (A-A') conduction band energy

* The Advanced Power Electronics Research Center, the National Institute of Advanced Industrial Science and Technology (seconded from Fuji Electric)

‡ Electronic Devices Business Group, Fuji Electric Co., Ltd.

reliability. In the 1.2-kV breakdown voltage class, channel resistance makes up the greatest proportion of the on-resistance components, even with a trench gate structure. Reducing channel resistance is therefore effective in reducing on-resistance. It is believed that one method of reducing channel resistance is to shorten the channel length L_{ch}. By shortening the channel length, however, a depletion layer penetrates both ends of the channel, causing a drop in conduction band energy levels as shown in Fig. 2. As a result, noise immunity deteriorates due to the drop in threshold voltage*1, and breakdown voltage drops due to p base layer punchthrough. The problem which arises by shortening the channel length in this way is known as "short-channel effects"(5)-(7).

3. Halo Structure

Research into short-channel effects as one of the issues involved in the miniaturization of horizontal silicon MOSFET has been ongoing since the mid-twentieth century, and a halo structure is known to be a suppression technology(8),(9).

Figure 3 shows a halo structure for horizontal MOSFET and a formation method involving tilt angle ion implantation.

A halo structure prevents penetration of the depletion layer from both ends of the channel by forming a p layer with higher concentration than that of the channel near the channel to suppress short-channel effects [see Fig. 3(a)]. Note that as there is no change in the carrier concentration of the channel layer directly beneath the MOSFET, there is no deterioration in channel mobility, or increase in on-resistance. A halo structure suppresses variations in distance from the channel ends and channel surface. To prevent any impact on device characteristics, tilt angle ion implantation is performed, and a halo structure is formed with cell alignment using a polysilicon gate for the shadow mask in the case of silicon-based horizontal MOSFETs [see Fig. 3(b)].

If applying a halo structure to vertical SiC trench gate MOSFETs, on the other hand, it is necessary to form a channel on the trench side wall. Furthermore, taking the thermal history of the process into consideration, it is necessary to form the halo structure prior to forming the polysilicon gate. It is therefore not possible to use the existing halo structure formation process as is. Accordingly, we devised a device structure in which a halo structure is formed on the source side only [see Fig. 4(a)]. To be more specific, we used the angle of the gate trench as a shadow mask, and performed tilt angle ion implantation on the trench side wall [see Fig. 4(b)]. The distance from the channel surface is determined by the tilt angle ion implantation energy, and the distance from the channel ends is determined by the tilt angle ion implantation angle, allowing formation by self-alignment with respect to the trench shape.

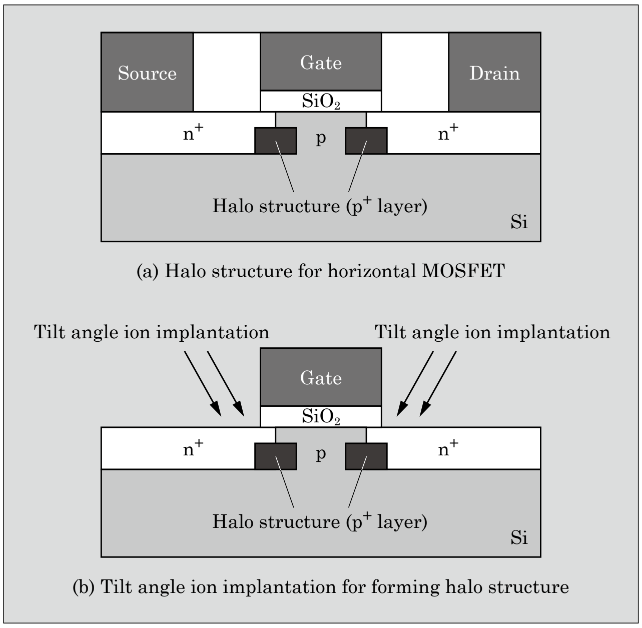

Fig.3 Halo structure for horizontal MOSFET and tilt angle ion implantation for forming halo structure

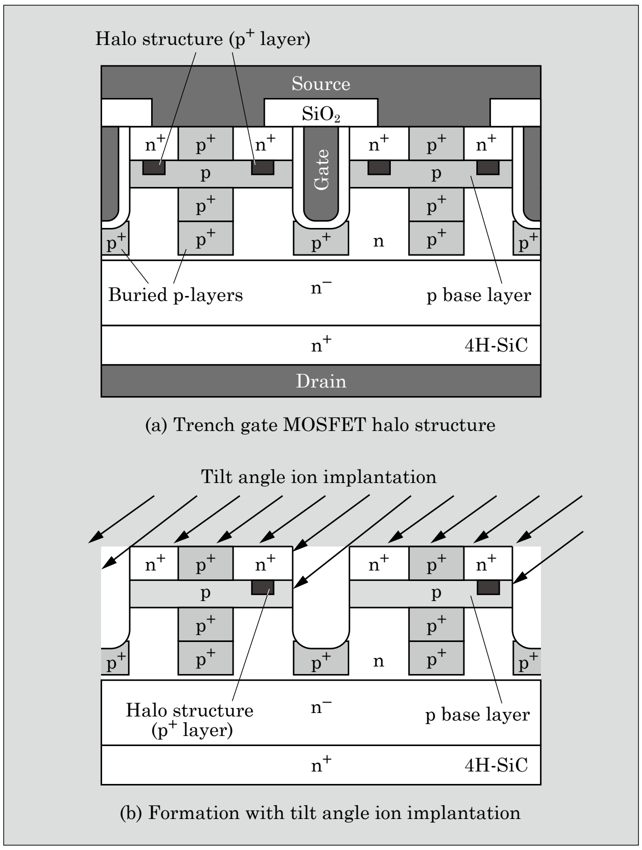

Fig.4 Trench gate MOSFET halo structure and formation with tilt angle ion implantation

*1: Threshold voltage: Voltage value between gate and source necessary to turn on MOSFET

4. Prototype Results

We carried out a simulation, and produced a prototype of a 1.2-kV breakdown voltage class vertical trench gate MOSFET with halo structure. Thereafter, we produced a prototype of a 4-inch wafer using a TPEC*2 manufacturing line. The threshold voltage channel length dependency is shown in Fig. 5. Without a halo structure, we find that there is a sharp drop in threshold voltage due to an increase in short-channel effects as the channel length shortens. By applying a halo structure, on the other hand, we find that we are able to suppress the drop in threshold voltage due to short-channel effects.

Due to the high power supply voltage of several hundreds of voltage or higher, a high threshold voltage is required even with high drain voltage. Figure 6 shows threshold voltage drain voltage dependency. By applying a halo structure, we are able to suppress a phenomenon known as drain-induced-barrier-lowering (DIBL), one of the short-channel effects in which threshold voltage drops further when drain voltage is increased.

Figure 7 shows the breakdown voltage when p base concentration is changed. Breakdown voltage drops when p base layer punchthrough, one of the short-channel effects, occurs. When the p base concentration is low, the depletion layer inside the channel tends to expand easily, enhancing the short-channel effects. Consequently, breakdown voltage drops rapidly when the p base concentration is lowered without applying a halo structure. With a halo structure, on the other hand, breakdown voltage is maintained even when the p base concentration is lowered, allowing the drop in breakdown voltage caused by punchthrough to be suppressed.

The relationship between on-resistance for each structure and threshold voltage is shown in Fig. 8. Device characteristics of low on-resistance and high threshold voltage are preferable, and therefore the lower right direction in the diagram is the direction of improved trade-off. Shortening the channel length allows the on-resistance to be reduced as a result of the drop in channel resistance, however, without a halo structure, the threshold voltage also drops simultane-

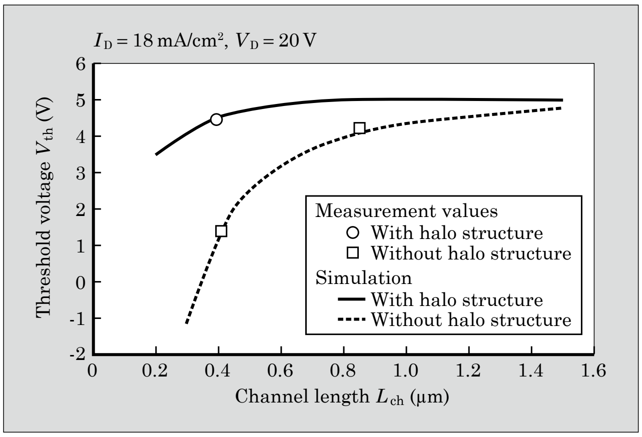

Fig.5 Threshold voltage when channel length changed

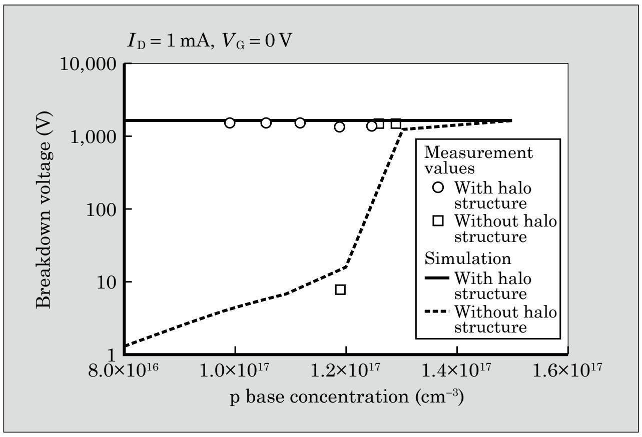

Fig.7 Breakdown voltage when p base concentration changed

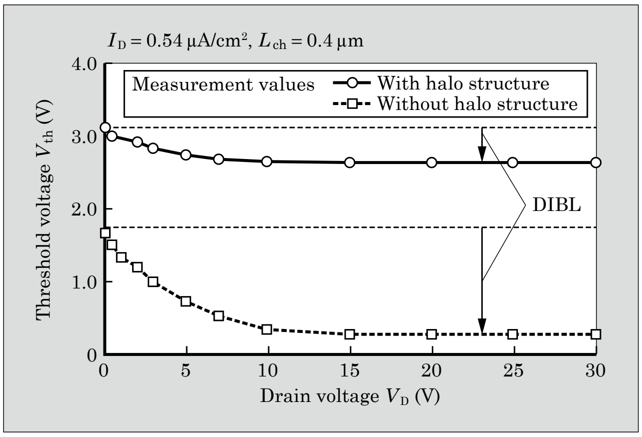

Fig.6 Threshold voltage when drain voltage changed

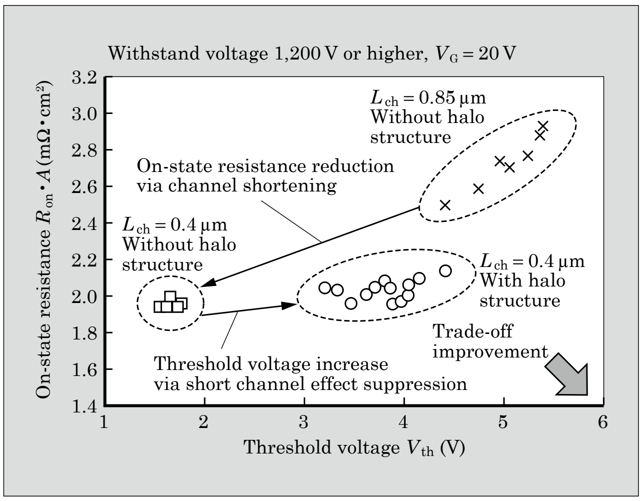

Fig.8 Relationship between on-resistance and threshold voltage

*2: TPEC: Joint research body Tsukuba Power Electronics Constellation ously. With a halo structure, on the other hand, even by shortening the channel length, the application of a halo structure simultaneously realizes a drop in on-resistance and high threshold voltage without any drop in threshold voltage, providing evidence of improved trade-off.

Figure 9 shows the internal allocation of each on-resistance element estimated from actual measurement and simulation. Without a halo structure, channel resistance contributes most, and is dominant. With a halo structure, a drop in on-resistance is achieved for elements with shortened channel length due to a drop in channel resistance. Note that the contribution ratio of the channel resistance becomes smaller than that of the drift layer and substrate resistance.

Figure 10 shows the relationship between short-circuit breaking time t_{sc} and on-resistance when the cell pitch of each structure is changed. Generally speaking, the longer the t_{sc} and lower the channel resistance, both relationships exhibit a trade-off even for SiC-MOSFET in the same way as that for Si-MOSFET. By using a halo structure, we find that t_{sc} is approximately 1.6 times longer even with the same on-resistance, and that the trade-off has improved.

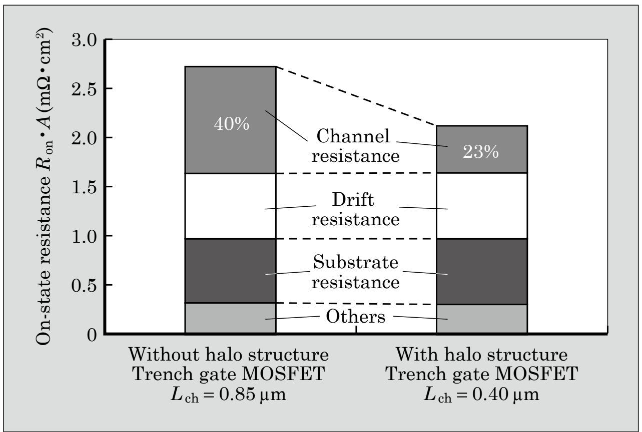

Fig.9 On-resistance of each structure and its components

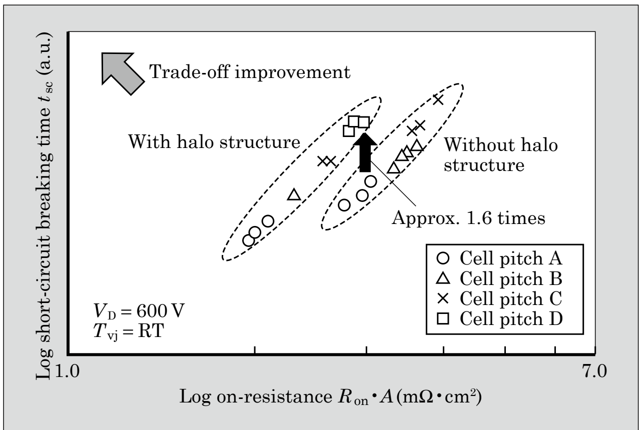

Fig.10 Relationship between short circuit capacity and on-resistance

5. Postscript

We described SiC-MOSFET, which achieved both high threshold voltage and low on-resistance using a halo structure. With a breakdown voltage of 1.2 kV, we produced a prototype of an SiC-MOSFET with halo structure and confirmed an improvement effect with the halo structure. To contribute to the realization of a low-carbon society, we will continue to pursue further reductions in SiC-MOSFET on-resistance and improvements in reliability.

This paper has been implemented under a joint research project of Tsukuba Power Electronics Constellations (TPEC). We would like to express our gratitude to all those concerned.

References

(1) Matsumoto, Y. et al. Power Electronics Equipment Applying SiC Devices. FUJI ELECTRIC REVIEW. 2015, vol.58, no.4, p.212-216.

(2) Oshima, M. et al. Mega Solar PCS Incorporating All-SiC Module “PVI1000 AJ-3/1000”. FUJI ELECTRIC REVIEW. 2015, vol.61, no.1, p.11-16.

(3) Harada, S. et al. “1200 V SiC IE-UMOSFET with Low On-resistance and High Threshold Voltage”, Materials Science Forum, 2017, vol. 897, p.497-500.

(4) Nakazawa, M. et al. All-SiC Modules Equipped with SiC Trench Gate MOSFETs. FUJI ELECTRIC REVIEW. 2017, vol.63, no.4, p.204-208.

(5) Noborio, M. et al. “Experimental and theoretical investigations on short-channel effects in 4H-SiC MOSFETs”. IEEE transactions on Electron Devices. 2005, vol.52, no.9, p.1954-1962.

(6) Kobayashi, Y. et al. Simulation Based Prediction of SiC Trench MOSFET Characteristics. FUJI ELECTRIC REVIEW. 2016, vol.62, no.1, p.12-16.

(7) Kobayashi, Y. et al. “Low on-resistance SiC trench MOSFET with suppressed short channel effect by halo implantation” ICSCRM, FR.D2.1, 2017.

(8) C. F. Codella; Ogura, S. “Halo doping effects in submicron DI-LDD device design”, IEDM, 1985.

(9) Y. Taur, E. J. Nowak. “CMOS devices below 0.1um: how high will performance go ?”. IEDM, 1997.

Fuji Electric

Innovating Energy Technology