2nd-Generation SJ-MOSFET for Automotive Applications "Super J MOS S2A Series"

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ABSTRACT

There has been increasing demand for smaller power conversion equipment and better fuel efficiency in eco-friendly vehicles such as hybrid electric vehicles. Accordingly, power MOSFET products are being required to be compact, low loss and low noise. Fuji Electric has developed and launched the "Super J MOS S1A Series," a product for automotive applications that adopt a superjunction structure characterized by their low on-state resistance and low switching loss. More recently, Fuji Electric has developed the 2nd-Generation SJ-MOSFET for automotive applications "Super J MOS S1A Series," which reduces conduction loss while improving the trade-off between switching loss and jumping voltage during turn-off switching. The use of this product contributes to size reduction and enhanced efficiency of the power conversion equipment for automotive applications.

1. Introduction

Recently, in the automotive market, eco-friendly vehicles represented by hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (P-HEVs) and electric vehicles (EVs) have been attracting attention as environmental regulations become increasingly stringent and users' environmental awareness rises. Efficient use of the electric power of the batteries mounted on these types of vehicles directly leads to an improvement in fuel efficiency, and power conversion technology (power electronics) is gaining importance. In addition, to improve the comfort of passengers by making the vehicle cabin more spacious, there is a strong demand to make automotive power converters smaller. Accordingly, power conversion equipment, such as automotive DC-DC converters and chargers, has to be compact, highly efficient and low-noise products. Semiconductor switching elements such as power metal-oxide-semiconductor field-effect transistors (MOSFETs) used in these types of power conversion equipment are also required to be compact, low loss and low noise.

In order to meet these requirements, Fuji Electric developed the 1st-Generation "Super J MOS S1 Series[(1)-(3)]" in 2011, which adopted a superjunction structure to achieve low on-state resistance and low switching loss; in 2014, we developed and commercialized the "Super J MOS S1A Series" (S1A Series), a discrete product for automotive applications.

This paper presents the 2nd-Generation SJ-MOSFET for automotive applications "Super J MOS S2A Series" (S2A Series) that features lower conduction loss than that of the S1A Series and suppresses the jump in the drain-source voltage V_{DS} (V_{DS} surge) in turn-off switching.

2. Design Concept

Figure 1 shows a breakdown of the loss generated in a power MOSFET in a power factor correction (PFC) circuit of a charger for automotive applications. The generated loss of a power MOSFET can be roughly classified into conduction loss P_{on} and switching loss consisting of turn-on loss P_{ton} and turn-off loss P_{toff}. To improve the efficiency of power conversion equipment, both the conduction loss and switching loss should be reduced. The conduction loss is reduced by lowering the on-state resistance, and the switching loss is reduced by increasing the switching speed. However, increasing the switching speed on the turn-off side in order to reduce the switching loss causes V_{DS} surge to increase during turn-off switching, and false turn-on may occur due to gate oscillation, which poses an issue.

Accordingly, the S2A Series aims to reduce conduction loss by reducing the on-state resistance per unit area, $R_{on}{\cdot}A$, to less than that of the S1A Series, and

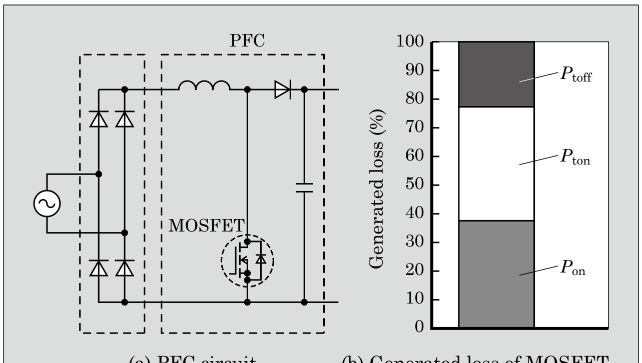

Fig.1 Generated loss of MOSFET in PFC circuit of charger

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improve the trade-off by reducing V_{DS} surge without increasing switching loss.

3. Features

3.1 Reduction of conduction loss

Since lowering the on-state resistance is effective in reducing the conduction loss, we have worked on decreasing $R_{on}{\cdot}A$ of the S2A Series.

The superjunction structure applied to the S1A and S2A Series ensures withstand voltage with the entire drift layer by providing the n-type and p-type regions, which constitute the drift layer, alternately laid out. This allows the impurity concentration of the n-type regions in the drift layer to be increased even with the same withstand voltage as that of the conventional planar type. Thus, $R_{on}{\cdot}A$ can be significantly reduced (see Fig. 2[(4)-(8)]).

We have improved the technology of the impurity diffusion process to increase the impurity concentration in the n-type regions. This reduces the resistance value of the drift layer, and we have further reduced $R_{on}{\cdot}A$ of the S2A Series to lower than that of the S1A Series[(9),(10)]. Figure 3 shows a comparison of $R_{on}{\cdot}A$ between the S1A and S2A Serieses that have a withstand voltage of 600 V. $R_{on}{\cdot}A$ of the S2A Series is 15 mΩ·cm², which is 25% lower than that of the S1A Series, 20 mΩ·cm².

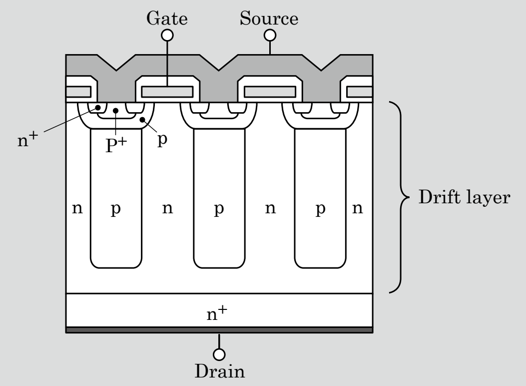

Fig.2 Superjunction structure

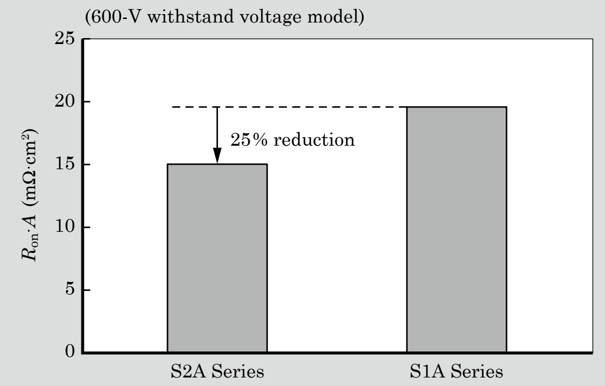

Fig.3 On-state resistance per unit area $R_{on}{\cdot}A$

3.2 Reduction of V_{DS} surge

As described in Section 2, reduction of switching loss and reduction of V_{DS} surge are in a trade-off relationship, and improving the relationship is an issue. The S2A Series reduces V_{DS} surge without increasing switching loss to improve the trade-off.

We often cannot design an ideal circuit pattern for a power board due to the restrictions that we have to use existing power circuit patterns, part layouts, and other conditions. In that case, if the circuit has large inductance and inappropriate drive conditions and circuit constants, simply replacing the MOSFETs increases V_{DS} surge, so that false turn-on may occur due to gate oscillation during switching.

As an example, we used a chopper circuit to compare the S1A Series and S2A Series. For ease of comparison, this circuit was not optimized in terms of the drive conditions and circuit constants according to the MOSFETs to use. Figure 4 shows the turn-off switching waveforms for the respective series. With the S1A Series, V_{DS} surge increases, causing a false turn-on [see Fig. 4 (a)].

Power converters for automotive applications are mounted in the engine room and often used in a high-temperature environment, and the threshold voltage $V_{GS(th)}$ has negative temperature characteristics. This leads to the assumption that FETs to be used are sus-

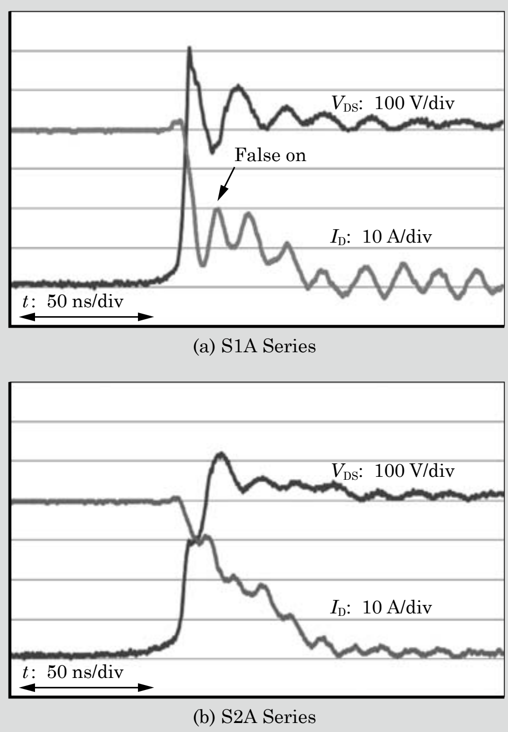

Fig.4 Turn-off switching waveforms (external gate resistance R_g: 2 Ω)

ceptible to gate oscillation and hence prone to false turn-on. It is considered effective to raise $V_{GS(th)}$ to suppress false turn-on. However, increasing $V_{GS(th)}$ alone causes V_{DS} surge to increase at the time of turn-off switching, leading to the possibility of a false turn-on due to gate oscillation.

The S2A Series have taken the countermeasures, including the optimization of $V_{GS(th)}$ and the integration of the gate resistance R_g into the chip, which increase $V_{GS(th)}$ while reducing V_{DS} surge to prevent false turn-on [see Fig. 4 (b)].

Figure 5 shows the characteristics of the external gate resistance R_g and V_{DS} surge evaluated by using the chopper circuit. When R_g is low, the S2A Series shows a V_{DS} surge-reducing effect as compared with the S1A Series. As shown in Fig. 6, the S2A Series shows a lower turn-off switching loss E_{toff} than that of the S1A Series at the same V_{DS} surge. This indicates that the trade-off between E_{toff} and V_{DS} surge has improved.

As explained up to now, when the MOSFET that has conventionally been used is replaced with a new one, reduction of V_{DS} surge eliminates the need for the user to change the circuit pattern or make significant changes to component constants. This facilitates the design of a high-efficiency power supply.

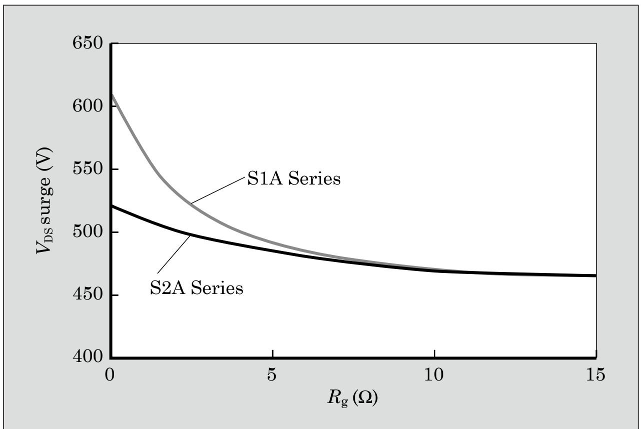

Fig.5 External gate resistance R_g and V_{DS} surge characteristics

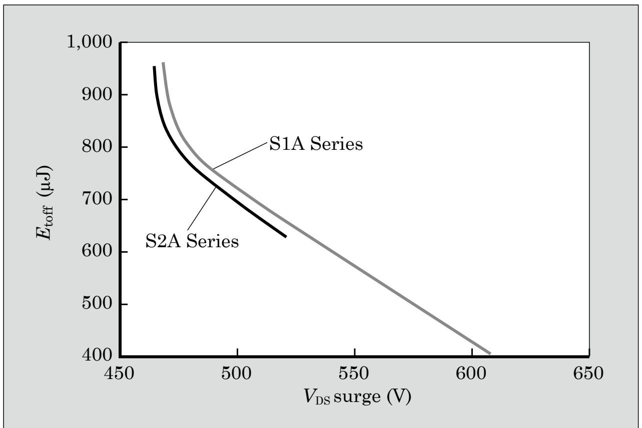

Fig.6 Turn-off switching loss E_{toff} and V_{DS} surge trade-off characteristics

It also expands the selection of element withstand voltages available, which has the effect of allowing the use of an element with a lower withstand voltage, or lower on-state resistance, than what has been used. Accordingly, we have commercialized the 500-V and 400-V withstand voltage models for the S2A Series, which had consisted of the 600-V and 650-V ones, equal voltages of the S1A Series models.

3.3 Reduction of loss under light load conditions

To extend the lifespan of batteries, DC-DC converters for automotive applications are driven under light load conditions in most of the lifetime operation. For that reason, reducing the loss under light load conditions significantly contributes to an improvement in fuel efficiency. When the DC-DC converter is operated under light load conditions, the current running through the MOSFET is small. Thus, the ratio of loss E_{oss} generated during charge and discharge to the output capacity C_{oss} accounts for a large proportion. Accordingly, with the S2A Series, the total gate electric charge Q_G has been reduced by optimizing the surface structure to successfully reduce E_{oss} by approximately 30% from that of the S1A Series (see Fig. 7).

The switching loss of the S2A Series has been reduced by improving the trade-off between E_{toff} and V_{DS} surge and reducing E_{oss}. This allows the power conversion circuit to be run at a higher frequency than conventionally done, which permits use of a smaller transformer, leading to miniaturization of power conversion equipment.

3.4 Quality for automotive applications

Products for automotive applications are required to have withstand capability against temperature changes. For the S1A and S2A Series, we worked on optimizing the chip thickness, the conditions of soldering under the chip during assembly, and the adhesion between the molding resin and lead frame. These measures significantly improved the temperature cycle capability as compared with consumer products with

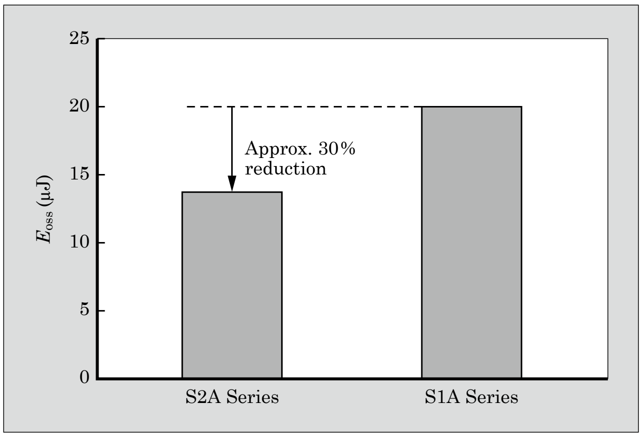

Fig.7 Loss generated in charge and discharge E_{oss}

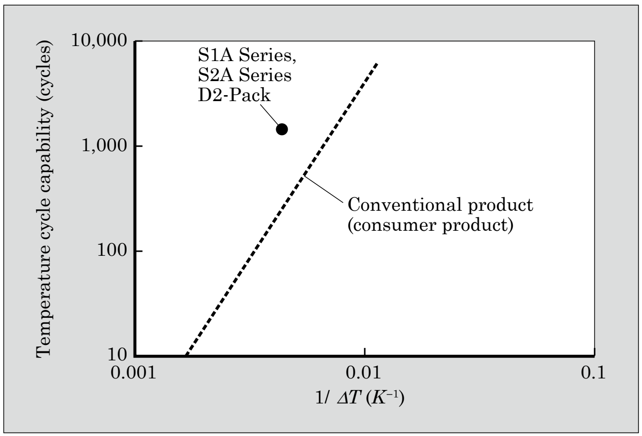

Fig.8 Temperature cycle capability

the same package and the same chip size (see Fig. 8).

4. Product Line-Up and Characteristics

Table 1 shows the product line-up of the S2A Series and major characteristics. In addition to improving the on-state resistance and switching characteristics described up to now, compliance with the AEC Q101 standard, which is a standard for reliability assurance of automotive discrete products, is guaranteed for the entire product line.

While the S1A Series using the TO-247 package has a minimum value of the on-state resistance of 40 mΩ for 600-V withstand voltage models, the S2A Series achieves 25.4 mΩ. The small surface-mount device (SMD) T-Pack (D2-Pack) of the S1A Series has an on-state resistance of 145 mΩ with 600-V withstand voltage models. The S2A Series, which can achieve 79 mΩ, contributes to miniaturization of power conversion equipment in terms of the package size.

Table 1 "Super J MOS S2A Series" product line-up and major characteristics

V_{DS}	$R_{DS(on)}$ max.	I_D	FRED	TO-247 	T-Pack (D2-Pack) 
400 V	60 mΩ	42 A	Available	—	FMC40N060S2FDA
500 V	71 mΩ	39 A	Available	FMY50N071S2FDA	FMC50N071S2FDA
600 V	25.4 mΩ	95 A		FMY60N025S2A	—
	40 mΩ	66 A		FMY60N040S2A	—
	70 mΩ	39 A		FMY60N070S2A	—
	79 mΩ	37 A		FMY60N079S2A	FMC60N079S2A
	81 mΩ	36 A	Available	FMY60N081S2FDA	FMC60N081S2FDA
	88 mΩ	33 A		FMY60N088S2A	FMC60N088S2A
	99 mΩ	29 A		FMY60N099S2A	FMC60N099S2A
	105 mΩ	28 A	Available	FMY60N105S2FDA	FMC60N105S2FDA
	125 mΩ	23 A		FMY60N125S2A	FMC60N125S2A
	133 mΩ	22 A	Available	FMY60N133S2FDA	FMC60N133S2FDA
	160 mΩ	18 A		FMY60N160S2A	FMC60N160S2A

Products with an on-state resistance of 25.4 to 160 mΩ with the TO-247 package and 81 to 160 mΩ with T-Pack are included in the product line. We have also launched the fast recovery diode (FRED) type "Super J MOS S2FDA Series," which integrates faster built-in diodes than those incorporated in the S2A Series.

5. Postscript

The 2nd-Generation SJ-MOSFETs for automotive applications "Super J MOS S2A Series" is a line of products achieving both low loss and reduced V_{DS} surge. They make significant contributions to efficiency improvement and miniaturization of power conversion equipment.

In the future, in order to meet increasingly advanced market needs, we intend to work on chip miniaturization and on-state resistance reduction. We will do so by expanding the product line with a wider selection of withstand voltages and further refining the superjunction structure to develop high-performance, high-quality discrete products for automotive applications.

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