Development of Power Devices for Automotive 1200V IPM Series

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Abstract

We have developed the SAM2 series of intelligent power modules (IPMs), which integrate power devices, control ICs equipped with drive and protection functions, and temperature-sensing thermistors within a transfer-molded package. These modules contribute to the miniaturization and improved energy efficiency of inverter units used for motor control in automotive and industrial air-conditioning systems. To address increasingly diverse market requirements, we are expanding our product lineup to include devices rated at 1200 V. This paper presents newly developed 1200V power devices intended for automotive applications and the corresponding SAM2 modules that incorporate these devices, designed specifically for electric water-pump driver systems.

1. Introduction

Power devices are semiconductor switching components used to control, convert, and distribute electrical power. As environmental concerns continue to intensify, the importance of power devices in power electronics — technologies that facilitate the efficient utilization of energy resources — has grown significantly.

We have focused on developing power device processes centered around the 600V class, and has produced products incorporating in-house IGBTs and FRDs. These products have been commercialized across a wide range of applications, from consumer electronics such as air conditioners and IH heaters to industrial equipment like inverters and UPS systems, as well as automotive applications.

Leveraging the technologies and experience cultivated through the development of IPMs for consumer air conditioners, we have commercialized the SAM2 series — transfer-molded IPMs equipped with high-voltage, high-current power devices, control ICs, and thermistors — for industrial and automotive air conditioning systems[1].

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To meet the growing demand for product diversity and expanded applications, we have also developed 1200V-class power devices and associated packaging technologies, and have launched 1200V-rated SAM2 products for industrial equipment[2].

Table 1 shows the SAM2 series products, and Figure 1 illustrates the development trends for automotive SAM2 series.

In recent xEVs (electric vehicles), systems that circulate coolant using electric water pumps have emerged. To add SAM2 power modules for controlling these systems to our lineup, we are developing 1200V IGBTs and FRDs with rated currents of 15A or less. For water pump cooling system applications, low-loss characteristics and high-response drive performance are required.

Table 1. SAM2 series products

Product name	Specification	Application	Status
SAM265M30AA1	650V/30A	Automotive	In Mass Production
SAM265M50AA1	650V/50A	Automotive	In Mass Production
SAM265M50BS3	650V/50A	Industrial	In Mass Production
SAM265M50AS3	650V/50A	Automotive	In Mass Production
SAM212M05BF1	1200V/5A	Industrial	In Mass Production
SAM212M10BF1	1200V/10A	Industrial	In Mass Production
SAM212M15BF1	1200V/15A	Industrial	In Mass Production
SAM212M05AF1	1200V/5A	Automotive	Under Development
SAM212M10AF1	1200V/10A	Automotive	Under Development
SAM212M15AF1	1200V/15A	Automotive	In Mass Production
SAM212M25AF1	1200V/25A	Automotive	Under Development

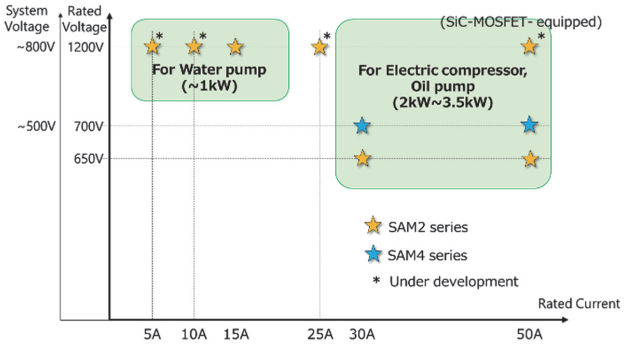


Figure 1. Development trends for automotive SAM2 series

2. Product Overview

The SAM2 products are three-phase inverter IPMs with a transfer-molded structure, incorporating IGBTs and FRDs as output switching elements, pre-driver ICs, bootstrap diodes with limiting resistors, and temperature-sensing thermistors. Figure 2 shows the appearance of SAM2 series products. The package design ensures sufficient insulation distance to support the 1200V rating.

Key features common to the SAM2 series include:

- Maximum control voltage rating: 25V
- Insulation withstand voltage: 2500V (1 minute)
- Built-in thermistor
- Various protection functions
- Adjustable overcurrent protection hold time
- Guaranteed operating temperature for IGBT and FRD: T_j = 175°C

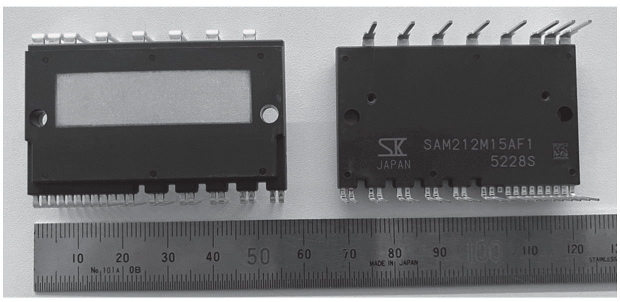


Figure 2. Appearance of SAM2 Series Products

Figure 3 shows a typical application circuit using a single shunt resistor for the automotive 1200V/15A-rated product SAM212M15AF1. The IGBTs are driven by signals from the controller on the left side of the diagram, enabling control of high voltage and high current. This allows the conduction state and current direction of the motor output terminals U, V, and W to be changed, enabling motor drive tailored to the customer's usage conditions.

The product also includes system-supporting features such as overcurrent protection and temperature monitoring via the built-in thermistor. These features enable feedback to the controller, which is a key characteristic of the product.

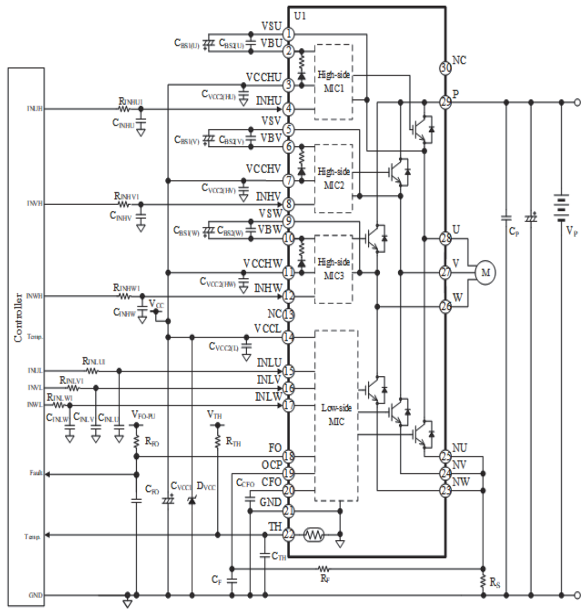


Figure 3. Typical Application Circuit using a Single Shunt Resistor

3. Development of 1200V Power Devices

3.1 1200V FS-IGBT Chip Technology

For the 1200V-rated IGBT, we adopted a Field Stop (FS) structure by thinning the wafer, established a stable thinning process, refined and optimized the trench gate structure, and improved the backside structure[3]. These efforts enabled both high withstand voltage and low loss characteristics. As a result, we have begun mass production of current-rated SAM2 products for industrial applications. The features of the 1200V FS-IGBT for automotive use are described in the following section.

3.2 Features of Automotive 1200V FS-IGBT

(A) Rated Voltage Guarantee at Low Temperatures

In automotive applications, products must operate reliably under harsh conditions, including low temperatures down to −40°C. At low temperatures, lattice vibrations in the silicon crystal decrease, increasing the probability of impact ionization due to collisions between electrons and atoms. This result leads to a reduction in device withstand voltage. To address this, we optimized the thickness of the N drift layer in the IGBT structure to maintain withstand voltage even at low temperatures.

(B) High-Temperature Operation Guarantee (T_{jmax} = 175°C)

To ensure stable operation under high-temperature conditions, the junction temperature (T_j) of the IGBT is guaranteed up to 175°C. Figure 4 shows relationship between the junction temperature (T_j) and the collector-to-emitter leakage current (ICES) of a single IGBT chip at rated voltage 1200 V. Since excessive leakage current at high voltage can lead to thermal runaway, it is a critical indicator for ensuring the quality and reliability of power devices. In the development of 1200V SAM2 products, we optimized the chip structure to suppress leakage current even when Tj exceeds 175°C. As shown in Figure 4, the leakage current of the IGBT chip at 190°C is approximately 3mA, confirming that thermal runaway does not occur.

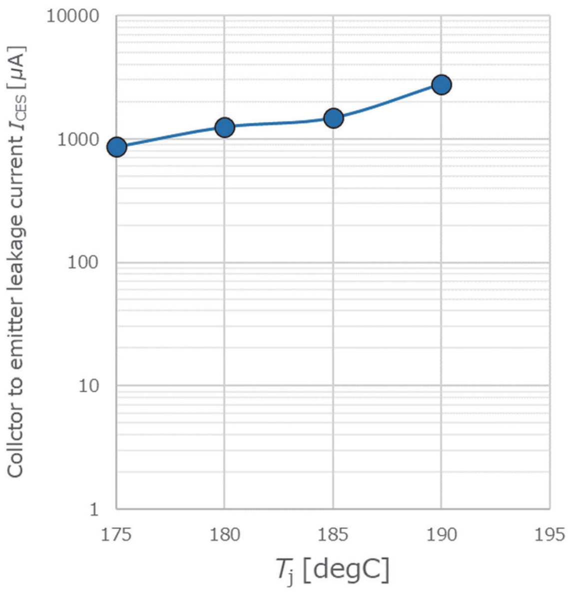


Figure 4. Collector-to-Emitter Leakage Current (I_{CES}) vs. Junction Temperature (T_j) at Rated Voltage 1200V for Single IGBT Chip

(C) Safe Operating Area Guarantee During Short-Circuit Conditions

IGBTs handle large amounts of power, so while reducing on-state voltage and turn-off switching losses, it is also necessary to ensure sufficient ruggedness. In cases of short circuits or failure of other components, the IGBT must withstand the current until the gate voltage is shut off by the protection circuit. By utilizing the current saturation characteristics of the IGBT, adjusting the channel region corresponding to the surface N-emitter layer, and optimizing the MOS structure, we suppressed the saturation current and ensured the required ruggedness.

(D) Approach to Automotive Quality Assurance

For automotive products, we conduct risk analysis on critical characteristics related to quality and safety, as well as customer requirements. Technical elements related to high-impact items are reflected in product design and specifications. In manufacturing, we manage key process parameters using Statistical Process Control (SPC). This approach enables not only the early detection and prevention of anomalies but also daily monitoring of process variation and control of process capability, thereby contributing to stable product quality.

3.3 1200V FRD Chip Technology

For the 1200V-rated FRD, a low-concentration anode structure was adopted, based on the active region structure of our 600V low-noise FRD[4]. By implementing lifetime control techniques, both low loss and soft recovery characteristics were achieved. The features of the 1200V FRD for automotive applications are described in the next section.

3.4 Features of Automotive 1200V FRD

(A) Soft Recovery Characteristics

Figure 5 shows the active region structure of the 1200V automotive FRD. To suppress switching noise in the product, the bottom of the drift layer was designed with a gentle concentration gradient in the N layer, which moderates abrupt carrier disappearance and enables soft-recovery behavior. The low-concentration anode structure suppresses hole injection, and optimization of lifetime control through particle irradiation contributes to reduced losses.

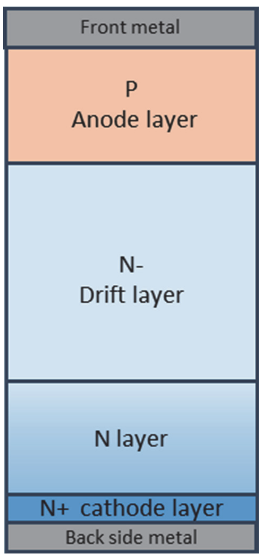


Figure 5. Active region structure of 1200V automotive FRD

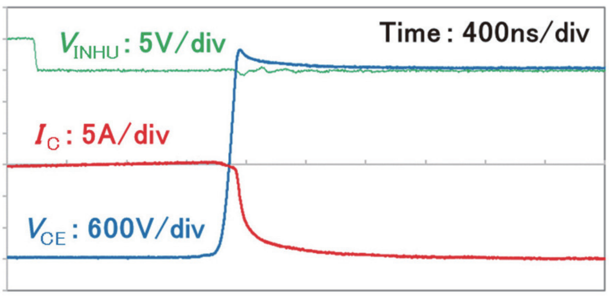
(B) Rated Voltage Guarantee at Low Temperatures and Suppression of Forward Recovery Voltage

To maintain rated voltage at −40°C, the N drift layer must be thickened. However, this increases the forward recovery voltage(2). When IGBT is turned off, carriers are injected into the high-resistance N drift layer of the FRD, and conductivity modulation gradually lowers the resistance. Immediately after turn-off, the resistance remains high, causing the forward recovery voltage to rise. This voltage can be applied as a negative potential to the high-side driver IC, potentially causing malfunction. Therefore, the thickness and carrier concentration of the N layer were optimized to balance low-temperature withstand voltage retention with suppression of the forward recovery voltage.

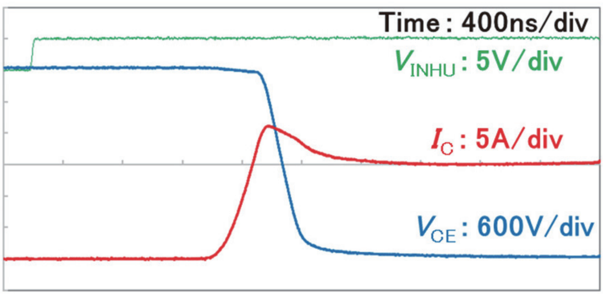
4. Product Evaluation Results

4.1 Switching and Electrical Characteristics

Switching tests were conducted on the automotive-grade SAM2 product, SAM212M15AF1, rated at 1200V/15A. The test waveforms are shown in Figure 6. Stable high-temperature operation was confirmed at a junction temperature of T_j = 175°C. The switching losses and soft recovery characteristics met the product targets. Detailed electrical characteristics are summarized in Table 2.



(a) High-side switching turn-off waveform



(b) High-side switching turn-on waveform

Vertical axis : V_{INHU}, V_{ce}, I_C, Horizontal axis : Time
Conditions : V_P = 600V, V_{CC} = 15V, I_c = 15A, T_j = 175℃

Figure 6. Switching waveforms

4.2 Conducted Noise Characteristics

The influence of current and voltage generated by inverter switching operations was evaluated across various frequency bands. The conducted noise characteristics are shown in Figure 7. The product complies with the CISPR22 Class B standard, confirming that the balance between switching losses and noise performance has been appropriately optimized.

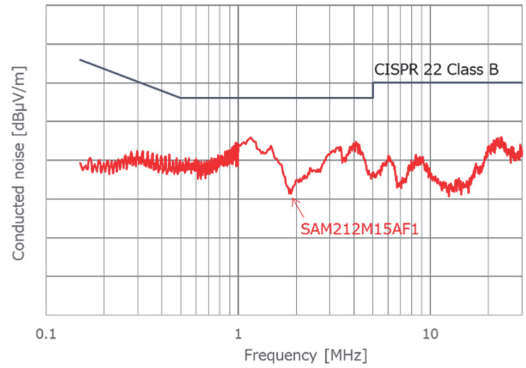
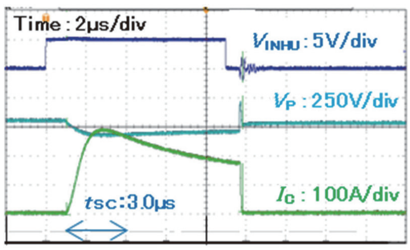


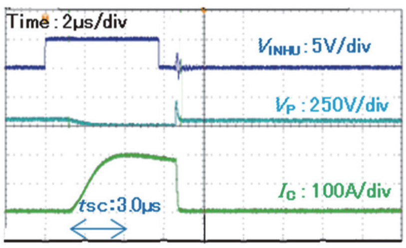
Figure 7. Conducted noise characteristics

4.3 Short-Circuit Testing

Figure 8 shows the waveforms from short-circuit testing. Under both low-temperature (−40°C) and high-temperature (175°C) conditions, the product withstood short-circuit current without damage during the short-circuit current duration of t_{sc} = 3.0μs, which is the target value. This confirms that sufficient short-circuit ruggedness is ensured across the full temperature range.



(a) At T_j = −40℃



(b) At T_j = 175℃

Vertical axis : V_{INHU}, V_P, I_C, Horizontal axis : Time
Conditions : V_P = 800V, V_{CC} = 16.5V

Figure 8. Short-circuit waveforms

Table2. Transistor characteristics of SAM12M15AF1

Parameter	Symbol	Conditions	Min.	Typ.	Max.	Unit
Collector-to-Emitter Leakage Current	I_{CES}	V_{CE} = 1200 V, T_j=25 ℃	—	—	0.1	mA
Collector-to-Emitter Saturation Voltage	$V_{CE(SAT)}$	I_C = 15 A, T_j = 25 ℃	—	1.7	2.2	V
		I_C = 15A, T_j = 125 ℃	—	2.1	2.7	V
Diode Forward Voltage Drop	V_F	I_F = 15A, T_j = 25 ℃	—	2.1	2.6	V
High-side Switching Characteristics						
Diode Reverse Recovery Time	t_{rr}	$V_{P(DC)}$ = 600 V, I_C = 15 A, V_{IN} = 0 ↔ 5 V, T_J = 25 ℃, Inductive load	—	0.50	—	μs
Turn-on Time	t_{ON}		—	1.25	—	μs
Turn-on Switching Time	$t_{C(ON)}$		—	0.45	—	μs
Turn-off Time	t_{OFF}		—	1.30	—	μs
Turn-off Switching Time	$t_{C(OFF)}$		—	0.30	—	μs
Low-side Switching Characteristics						
Diode Reverse Recovery Time	t_{rr}	$V_{P(DC)}$ = 600 V, I_C = 15 A, V_{IN} = 0 ↔ 5 V, T_J = 25 ℃, Inductive load	—	0.45	—	μs
Turn-on Time	t_{ON}		—	0.90	—	μs
Turn-on Switching Time	$t_{C(ON)}$		—	0.45	—	μs
Turn-off Time	t_{OFF}		—	0.90	—	μs
Turn-off Switching Time	$t_{C(OFF)}$		—	0.30	—	μs

4.4 Reliability Evaluation

The SAM212M15AF1 automotive-grade SAM2 product, rated at 1200V/15A, underwent comprehensive reliability evaluations conducted in accordance with the guidelines of IEC, JEITA, and AQG324. The results confirmed that the product meets all required standards without any issues.

5. Conclusion

To support the integration of IPM motor driver products for automotive applications, we developed new 1200V power devices — IGBTs and FRDs. As a result, we commercialized the SAM2 product SAM212M15AF1, rated at 1200V/15A, thereby expanding the SAM2 series lineup.

Moving forward, we plan to sequentially mass-produce products with current ratings comparable to those for industrial equipment. In addition, we will continue to develop power devices and packaging technologies to further expand the lineup of 1200V-rated IPM products for high-current applications.

References

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