Automotive Diodes

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1. Introduction

Environmental problems and the need to conserve energy are powerful factors that have advanced the development of electric vehicles and hybrid electric vehicles in the automotive field. In particular, because hybrid electric vehicles require only a supply of fuel and do not need special charging equipment (eco-stations), the quantity of production and range of model types of hybrid vehicles have been increasing year-by-year. A hybrid vehicle is equipped with, in addition to an engine, a motor, a high-voltage high-power battery to drive that motor, and a DC-DC converter to convert the voltage from a main battery and to supply that voltage as a low voltage source to conventional electronic autoparts. It is important that DC-DC converters for hybrid electric vehicles have high efficiency, small size and high reliability, and because DC-DC converters that handle large currents are likely to become a source of noise, it is also important that consideration be given to anti-noise capability.

This paper introduces Fuji Electric's high-voltage, low loss and low noise product line of diodes that have been developed for use in DC-DC converters in accordance with the growing use of electronic control units (ECUs) due to the increasing use of electronic components and systems in automobiles, and also introduces a high-voltage highly reliable diode that is being used in distributorless ignition systems (DLIS), an increasingly popular form of electronic ignition systems.

2. High-voltage SBD

2.1 Overview

Fuji Electric's newly developed Schottky barrier diode (SBD) is considered to be the ideal diode for power supply rectification and especially well suited for high voltage output rectification. Low-voltage SBDs (30 V and 45 V) are being used in 3.3 V and 5 V low-voltage output circuits, and high-voltage LLDs (low loss fast recovery diodes) (200 V, 300 V and 400 V) have been used in 12 V and higher high-voltage output circuits. In order to support requests for larger capacity, smaller size and lower noise of 12 V and higher high-voltage outputs, reduction of the generated loss by improvement of the forward voltage (V_F) and reduction of the generated surge voltage and switching noise by improvement of the reverse recovery characteristic are required of diodes used in power supply rectification applications. An analysis of the loss occurring in a 12 V output stage diode in a power supply (250 W) that uses a 200 V LLD reveals that at least 90 % of loss is due to V_F. Moreover, to suppress the surge voltage applied to a diode during switching and to suppress the noise generated by the steep dv/dt characteristic, additional components such as snubber circuits and EMI-suppressing beads have been used, but doing so increases the part count and leads to higher cost.

The LLDs used previously were pn junction diodes and there was a limit to the extent which their V_F could be lowered. Also, there was a general tradeoff relation (reverse correlation) between soft recovery characteristics and V_F, and it was extremely difficult to realize both low V_F and soft recovery. Therefore, in recognition of the low V_F and soft recovery characteristics of SBDs, by using a high-voltage SBD instead of the high-speed pn diode that had conventionally been used in high-voltage output circuits, lower loss and lower noise due to the soft recovery characteristics could be achieved simultaneously. Accordingly, the new high-voltage SBD targeted output stage applications ranging from 12 V to 48 V and, in contrast to the existing high-speed pn diode, was developed to:

(1) ensure lower V_F characteristics,
(2) ensure a soft recovery, and
(3) have a V_{RRM} (or working voltage) of 120 to 250 V.

2.2 Chip design

(1) Chip edge design

Figure 1 shows the structure of a high-voltage SBD chip. The chip edge design utilizes a guard ring process. The breakdown voltage of the device is determined by the resistivity ρ and thickness t of the epitaxial layer (n-layer). Figure 2 shows the dependency of breakdown voltage (V_{BR}) on resistivity ρ and thickness t. Higher resistivity ρ and a greater thickness t of the epitaxial layer were designed to achieve a higher breakdown voltage. Furthermore, the desired working voltage was secured by optimizing the concentration and diffusion depth of the guard ring.

(2) Selection of barrier metal

Based on the considerations of paragraph (1) above, in order to secure a working voltage range of 120 to 250 V, it was necessary to increase the resistivity and to achieve an epitaxial layer thickness of at least 10 µm. Assuming the same type of unipolar operation as a low-voltage SBD, V_F would be expected

Fig.1 Cross-section of SBD chip structure

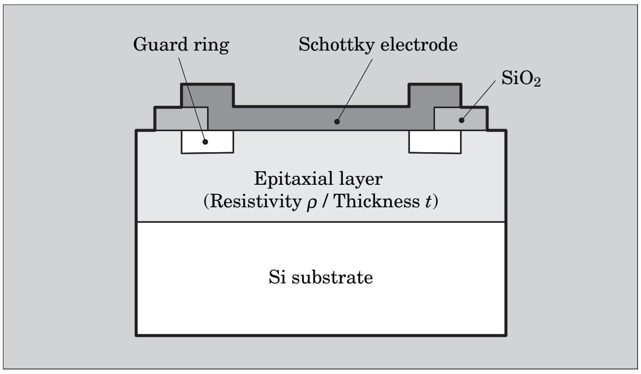
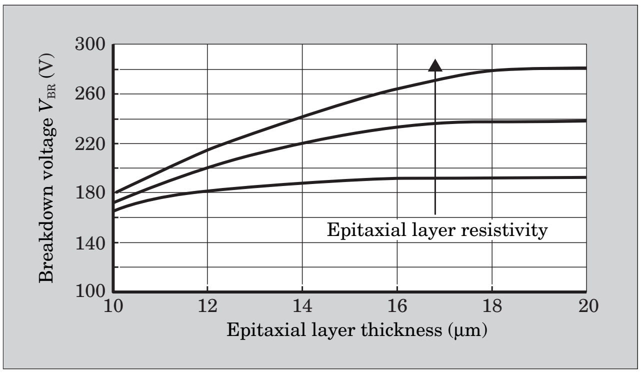


Fig.2 Relation between epitaxial layer thickness and breakdown voltage



to become considerably larger than that of a pn diode, however the injection of minority carriers (holes) from Schottky contacts and the guard ring acts to suppress V_F. Below we shall verify how the selection of barrier metal changes the forward characteristics. Figure 3 shows the simulated results of the forward characteristics for three types of barrier metals a, b and c (having barrier heights of a<b<c) fabricated in 40 V, 150 V and 250 V epitaxial layers. For the 150 V and 250 V epitaxial layers, in the region of high current flow, V_F decreased as barrier height increased (and the plotted curves intersected between 0.7 and 0.8 V). Hole injection from the Schottky contacts increased as the resistivity and/or barrier height of the epitaxial layer increased. Figure 4 shows the relation between V_F and I_R (V_F-I_R characteristics obtained by varying the barrier height for each voltage class) based on the results of Fig. 3. The 40 V class exhibits the usual V_F-I_R characteristic tradeoff, but at 150 V and 250 V, V_F decreases as barrier height increases. It is thought that the characteristics at 120 V are similar to those at 150 V. Moreover, in a 250 V SBD, a barrier height of metal b or higher is required to achieve a lower V_F

Fig.4 Relation between forward voltage and reverse current

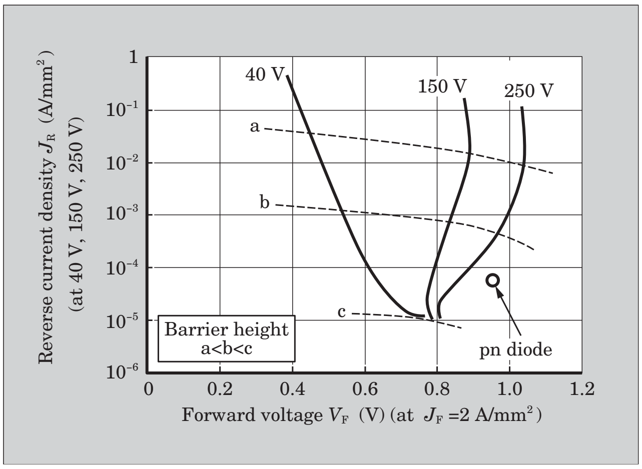


Fig.3 Simulated forward characteristics

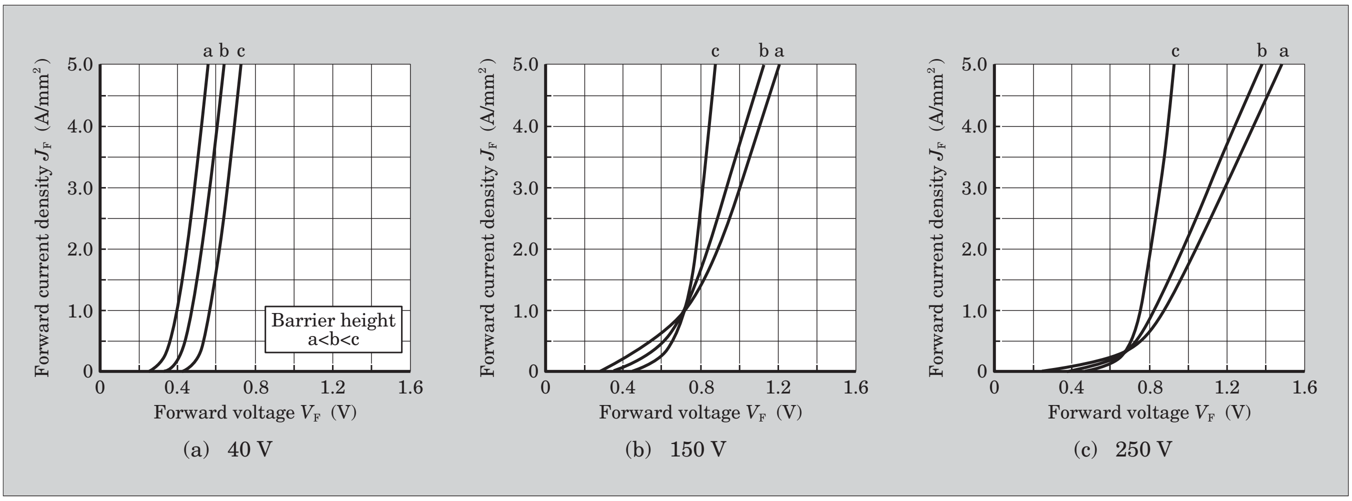


Fig.5 Forward and reverse characteristics of 120 V SBD (trial product)

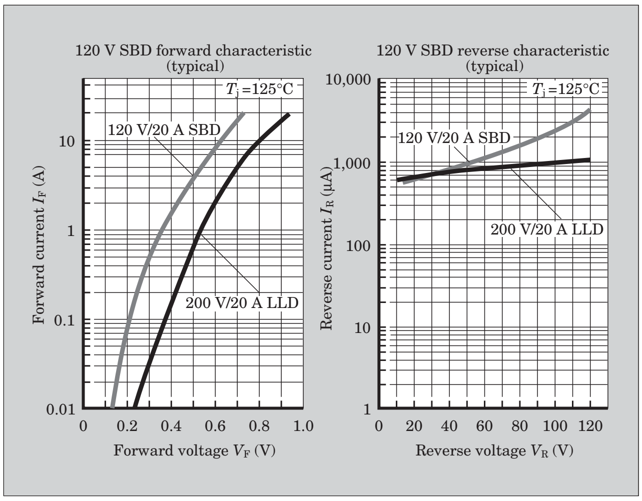
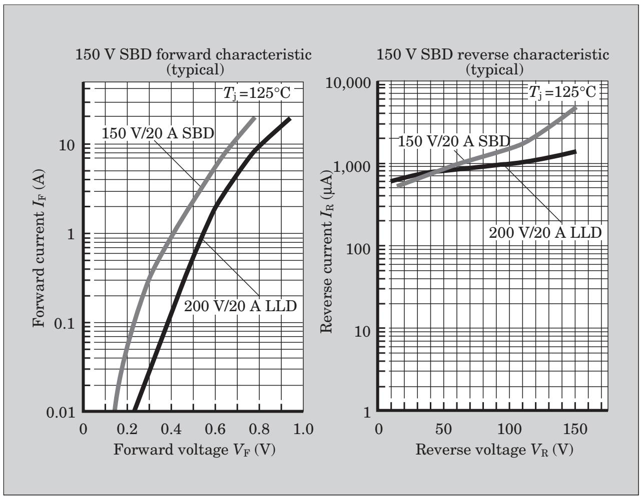


Fig.6 Forward and reverse characteristics of 150 V SBD (trial product)



characteristic than that of a pn diode.

2.3 Electrical characteristics

Based on the above considerations, we manufactured 120 V, 150 V and 250 V SBDs (having a rated current of 10 A). Figure 5 shows the forward and reverse characteristics of the 120 V SBD and Fig. 6 shows the forward and reverse characteristics of the 150 V SBD (where $T_j = 125°C$). Fuji Electric's 200 V LLD is shown for comparison. Both the 120 V and 150 V SBDs have lower V_F than the LLD. The low V_F is particularly noticeable in the low current region. Figure 7 shows a comparison of the reverse characteristics of a 150 V SBD and a 200 V LLD. It can be seen that the SBD has somewhat lower reverse peak current (I_{RP}) and has a softer recovery.

2.4 Actual circuit test results

Figure 8 shows a comparison of the diode waveforms in a 250 W 12 V output power supply test circuit using a 200 V LLD and also in the case of using a 150 V SBD. Figure 8(a) shows the evaluation circuit, and Figs. 8(b) and (c) show the forward waveforms of the diode. It can be seen that the SBD dramatically reduces surge voltage. A comparison of the loss calculated at the secondary-side diode in each of these cases is shown in Fig. 9. The SBD achieves an 18.3 % reduction in loss. 24 V and 48 V power supplies are expected to have similar results and an approximate

Fig.7 Reverse recovery characteristic (trial product)

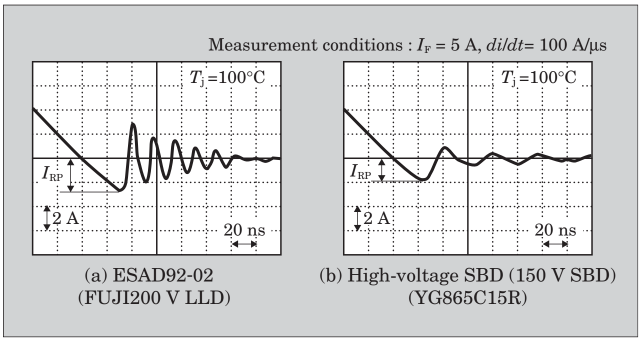


Fig.8 V and I waveforms of diode operation in 12 V output power supply circuit

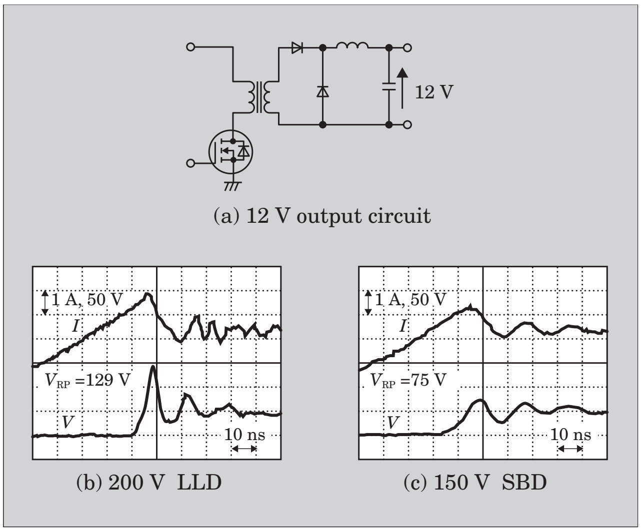


Fig.9 Loss comparison of 12 V output power supply secondary side diodes (simulated results)

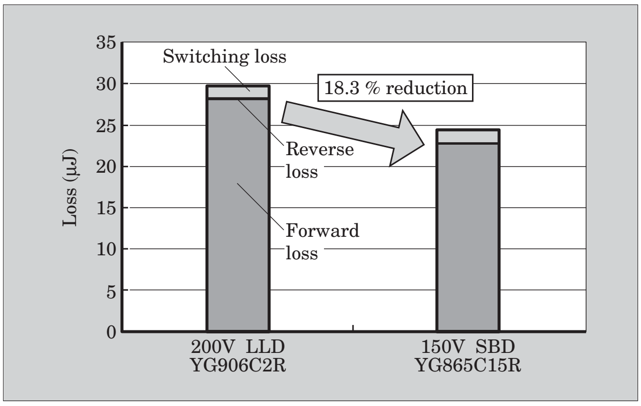


Table 1 High-voltage SBD product line

Model number	Package	Maximum rating			Electrical characteristic	
		V_{RRM} (V)	I_O (A)	I_{FSM} (A)	V_{FM} (V) $I_{FM}=0.5\times I_O$ (T_j = 25°C)	I_{RRM} (μA) $V_R=V_{RRM}$
YA862C12R	TO-220	120	10	75	0.88	150
YG862C12R	TO-220F	120	10	75	0.88	150
TS862C12R	T-Pack	120	10	75	0.88	150
YA865C12R	TO-220	120	20	150	0.88	150
YG865C12R	TO-220F	120	20	150	0.88	150
TS865C12R	T-Pack	120	20	150	0.88	150
YA868C12R	TO-220	120	30	225	0.88	200
YG868C12R	TO-220F	120	30	225	0.88	200
TS868C12R	T-Pack	120	30	225	0.88	200
YA862C15R	TO-220	150	10	75	0.90	150
YG862C15R	TO-220F	150	10	75	0.90	150
TS862C15R	T-Pack	150	10	75	0.90	150
YA865C15R	TO-220	150	20	150	0.90	150
YG865C15R	TO-220F	150	20	150	0.90	150
PH865C15	TO-247	150	20	150	0.90	150
TS865C15R	T-Pack	150	20	150	0.90	150
YA868C15R	TO-220	150	30	225	0.90	200
YG868C15R	TO-220F	150	30	225	0.90	200
PH868C15	TO-247	150	30	225	0.90	200
TS868C15R	T-Pack	150	30	225	0.90	200
YA862C25R	TO-220	250	10	75	1.08	150
YG862C25R	TO-220F	250	10	75	1.08	150
TS862C25R	T-Pack	250	10	75	1.08	150
YA865C25R	TO-220	250	20	150	1.08	150
YG865C25R	TO-220F	250	20	150	1.08	150
PH865C25	TO-247	250	20	150	1.08	150
TS865C25R	T-Pack	250	20	150	1.08	150
YA868C25R	TO-220	250	30	225	1.08	200
YG868C25R	TO-220F	250	30	225	1.08	200
PH868C25	TO-247	250	30	225	1.08	200
TS868C25R	T-Pack	250	30	225	1.08	200

20 to 30 % reduction in loss is anticipated.

2.5 Product lineup

Table 1 shows the high-voltage SBD product line-up. I_o ratings are 10 A, 20 A and 30 A and available packages are the TO-220, TO-220F, TO-247 and T-Pack (SMD).

3. High-voltage Diodes for DLIS-use

3.1 Overview

DLIS is a highly efficient system for electrically delivering a high voltage to individual spark plugs based on control signals from an electronic control unit (ECU), and is used to overcome the following disadvantages of the conventional distributor ignition system (in which a mechanical contact point rotates to deliver a high voltage to each spark plug):

(1) burnout and energy loss caused by sparks at the point of contact,
(2) the difficulty of achieving precise control at high rotational speeds, and
(3) the generation of electromagnetic noise and loss of ignition energy due to sparks at the point of contact and the use of a high tension ignition cable.

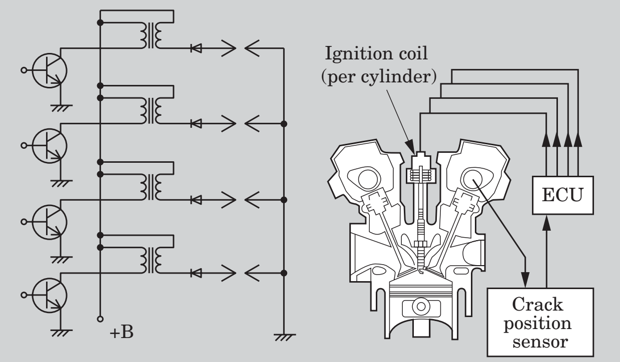
Figure 10 shows a circuit diagram of the coil distributed independent spark-type DLIS, which is the mainstream DLIS, and also shows a diagram of the ignition system. Below, the high-voltage diodes used in this coil distributed independent spark-type DLIS will be described.

3.2 Role of the high-voltage diode in a DLIS system and future challenges

In order to achieve high output voltage at the secondary coil, the abrupt change in magnetic flux in the coil caused by the turnoff of a primary-side ignition transistor is utilized. However, a voltage is naturally generated in the secondary coil while the transistor is in the on-state, and this voltage which is also applied to the spark plug may cause pre-sparking to occur at times other than the optimal sparking interval. A high-voltage diode may be used to prevent this on-state voltage and pre-sparking, however.

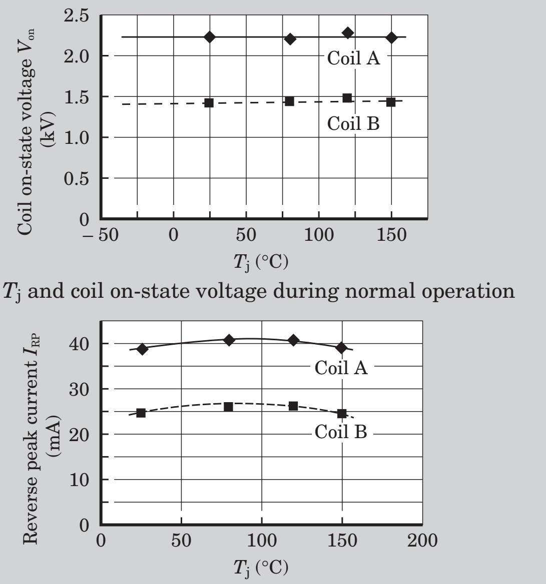
For this reason, a high-voltage diode is incorporated in the ignition coil close the spark plug in an engine block. In order to ensure reliability, it is important that the design has been made heat-resistant. It is also necessary to consider the surge voltage in the case of misfiring, and the provision of the device with surge-proof capability is an important challenge for the future.

Fig.10 Coil distributed spark-type DLIS



(a) Independent spark-type (b) Ignition systems diagram

Fig.11 Relation between T_j and V_{on} at normal operation and relation between T_j and I_{RP} at abnormal (open) operation



(a) T_j and coil on-state voltage during normal operation

(b) T_j and reverse peak current during open operation

3.3 Device design

(1) Breakdown voltage design

As an example of the results of an investigation of the voltage generated at the secondary side of the ignition coil during on-state operation of the transistor, Fig. 11(a) shows the relationship between diode junction temperature (T_j) and the voltage generated at the secondary side when I_c = 9 A. Based on these findings, the actual voltage is assumed to be 2.5 kV or less.

Next, we simulated an abnormal operating condition in which the spark plug was assumed to be open-circuited and examined the electrical stress of an HVD (high-voltage diode). When the plug is open-circuited, a high reverse bias of several tens of kV is applied to the high-voltage diode and loss is generated due to the avalanche voltage and reverse current.

Figure 11(b) shows the relationship between the peak value of reverse current and T_j during open operation. The pulse width of the reverse current was 100 µs or less. In the design stage, it has been proposed to make the V_{RRM} (or working voltage) of an element higher than the voltage generated at the secondary coil during open plug operation, but this is impractical because a large voltage of several tens of kV would be applied to the entire system in the case of an abnormal operation. Additionally, a design that increases the breakdown voltage would lead to greater forward loss and the generation of heat, and as such, is not the best solution.

On the other hand, decreasing the breakdown voltage leads to lower loss, and in consideration of safety as well, the optimal design would be one in which the specified breakdown voltage is reduced to the extent possible and reverse surge withstand capability is ensured. Such a design is capable of achieving a drastic reduction in the heat generated by a high-voltage diode and is well suited for realizing a high

Fig.12 Relation between pulse width and avalanche current withstand capability

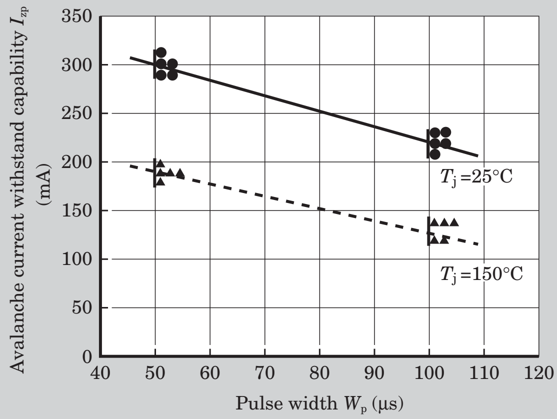


Table 2 Absolute maximum ratings and electrical characteristics of EJA28-02S, ESJA28-03 and ESJA27-02S

(a) Absolute maximum ratings

Item	Symbol	Rating			Unit	Condition
		ESJA28-02S	ESJA28-03	ESJA27-02S		
Repetitive peak reverse voltage	V_{RM}	2.2	2.7	2.2	kV_{peak}	Ignition pulse
Non-repetitive peak reverse voltage	V_{RSM}	2.5	3	2.5	kV_{peak}	Ignition pulse
Average forward current (half sine-wave average)	I_o	10	10	10	mA	f = 60 Hz, sine half-wave rectification
Non-repetitive peak forward current (10 ms)	I_{surge}	1	1	1	A_{peak}	f = 60 Hz, sine-half wave, 1 cycle
Junction temperature	T_j	150	150	150	°C	—
Storage temperature	T_{stg}	– 40 to +150	–40 to +150	–40 to +150	°C	—
Package size	—	ϕ2.5 × 6.5	ϕ2.5 × 6.5	ϕ2.5 × 6.5	mm	—

(b) Electrical characteristics

Item	Symbol	Rating			Unit	Measurement condition (at T_j = 25°C)
		ESJA28-02S	ESJA28-03	ESJA27-02S		
Forward voltage	V_F	≤7	≤8.4	≤7	V	I_F = 10 mA
Reverse current	I_{R1}	≤5	≤5	≤5	μA	– 02S : V_R = 2.2 kV – 03 : V_R = 2.7 kV
Reverse current	I_{R2}	≤10	≤10	≤10	μA	– 02S : V_R = 2.5 kV – 03 : V_R = 3.0 kV
Avalanche breakdown voltage	V_{av}	2.7≤	3.3≤	2.7≤	kV	I_{av} = 100 μA

heat-resistant design.

(2) Design for reverse surge withstand capability

The ability to withstand reverse surges is necessary because of the sudden reverse voltage that exceeds the avalanche voltage and is applied during open plug operation. To achieve high surge withstand capability with a sufficient margin to withstand surge currents during open operation, this product incorporates such measures as:

① optimized chip resistivity, chip area and insulation layer thickness,
② uniform silicon (Si) resistivity,
③ technology for achieving uniform p^+ and n^+ diffusion depths, and
④ technology for achieving uniform shape of the chip surface

and also reduces and equalizes the electric field intensity when an overvoltage is applied. Figure 12 shows the relationship between pulse width and avalanche current withstand capability.

(3) Design for high temperature operation

The quality of materials, structure of the mold resin, chip surface passivation and the like are important factors for usage in high temperature environments such as this application and in usage environments where the temperature differential is large and causes high thermal stress. Accordingly, Fuji Electric has achieved a high-temperature-resistant design by implementing such measures as:

① assessing the degradation in material properties over time by testing the properties of resin materials in a high temperature storage test,
② using the optimal external resin packaging based on heat shock tests, high temperature reverse bias tests and the like, and
③ adopting technology to ensure a proper and uniform thickness of the passivation layer.

3.4 Product introduction

Table 2 lists the maximum ratings and main electrical characteristics of Fuji Electric's DLIS prespark prevention high-voltage diode product line.

4. Conclusion

An overview of Fuji Electric's automotive diodes has been presented. Based on the products and technologies introduced herein, Fuji Electric intends to further expand its product line and is committed to advancing the development of even higher-grade products for the future.

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