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Fairchild's Second-Generation, Field-Stop, Shorted-Anode, Trench IGBTs for Induction Heating Applications

Summary

Fairchild recently developed a field-stop, shorted-anode, insulated-gate, bipolar transistor (IGBT) product family; ranging from 1100-1400 V and including an intrinsic body diode. Since the intrinsic anti-parallel diode is tailored to soft commutation, these new IGBTs are suitable for soft-switching applications such as induction cookers and inverterized microwave ovens. With advancements over the typical non-punch-through (NPT) IGBT technology, Fairchild's shorted-anode silicon technology offers lower saturation voltage, up to 12.5%, than same rating NPT trench IGBT and lower tail current, up to 36 %, than the same rating NPT trench IGBT.

Introduction

With the rapid progress in power semiconductors, each power electronics application has required dedicated semiconductor switching devices from both cost and performance standpoints. Although the operating frequency of IGBT is limited to the several tens of kHz due to its inevitably large tail current loss, it is very suitable for the high-power applications over 600 V voltage rating. The increment of saturation voltage drop, $V_{CE(sat)}$ in accordance with BV_{ces} is relatively smaller than other switching devices.

Today's most popular IGBT technology is Field-Stop IGBT (FS IGBT), which combines the advantages of PT (punch-through) and NPT (non-punch-through) IGBT structures, while overcoming the drawbacks of each structure. FS IGBT provides lower $V_{CE(sat)}$ during on-state and lower switching losses during the turn-off instant. However, since it doesn't include an intrinsic body diode in common with all other types of IGBTs, it is generally packaged together with an additional Fast Recovery Diode (FRD) for most switching applications.

Meanwhile, two types of resonant inverters, a half-bridge (HB) inverter and a single-ended (SE) inverter can be considered for induction heating applications. The SE resonant inverter is more commonly used due to its lower cost structure, relatively high efficiency, and ability to handle relatively high power ratings – up to about 2 kW.

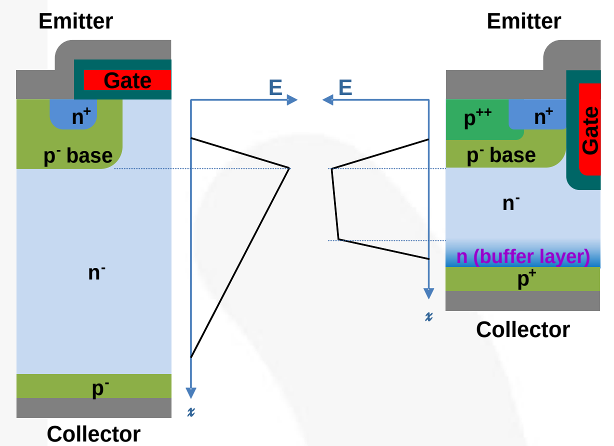


Figure 1. NPT IGBT (Left) and Field Stop IGBT (Right)

This application note introduces Fairchild's second-generation, field-stop, shorted-anode, trench IGBT family that has intrinsic body diode, unlike general IGBTs, and discusses its validity in the SE resonant inverter for induction heating (IH) applications.

Fairchild's New Field-Stop Shorted-Anode Trench IGBT Technology

Although NPT IGBT improves turn-off speed by reducing the minority carrier injection quantity and raising the recombination rate during the turn-off transition; it is undesirable for certain high-power applications due to its higher $V_{CE(sat)}$. Higher $V_{CE(sat)}$ is caused by the n^- drift layer being lightly doped and, consequently, the thicker drift layer is needed to sustain the electric field during the off state, as shown in Figure 1. The thickness of n^- drift layer is the dominant factor of the saturation voltage drop in IGBTs.

By means of inserting the n doped field-stop layer between the n- drift layer and the p^+ collector, as shown on the right side of Figure 1; the thickness of the n^- drift layer can be reduced. This is concept (and the IGBT applying the concept) is called Field Stop IGBT (FS IGBT). In the FS IGBT, the electric field rapidly decreases within the field-stop layer, while gradually decreasing within n^- drift layer. Therefore, the thickness of the n^- drift layer and the saturation voltage drop can be significantly reduced. The trench gate structure improves the saturation voltage drop. In addition, the field-stop layer accelerates the majority carrier recombination during the turn-off instance and, therefore, its tail current is much smaller than NPT or PT IGBTs. This leads lower switching losses.

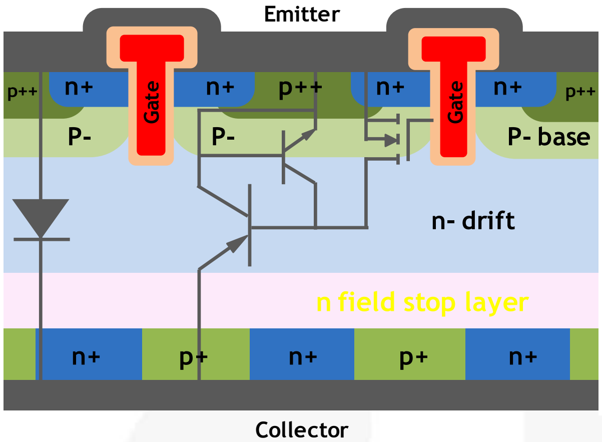
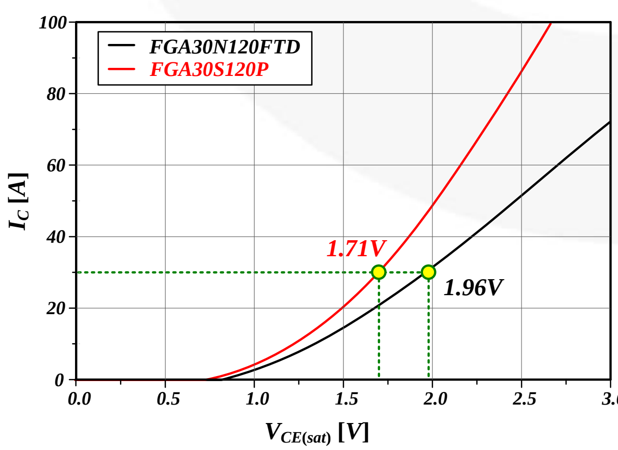


Figure 2. Cross Section of FS SA T IGBT

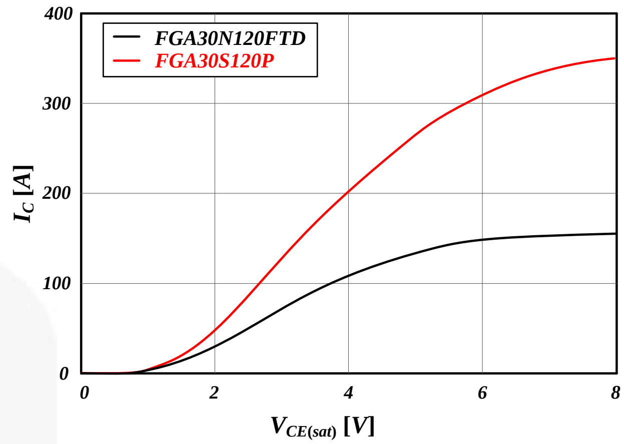
The conventional FS IGBT doesn't include the intrinsic body diode, similar to PT and NPT IGBTs, due to the p^-, n^-, n, p^+ structure. Therefore, it is packaged with an additional FRD for most applications. Recently, a new idea emerged, the shorted-anode IGBT (SA IGBT), which embeds the body diode into IGBT in the same fashion as the metal-oxide semiconductor field-effect transistor (MOSFET).

Figure 2 shows the concept that grafts the shorted anode onto the field-stop trench IGBT. The idea behind the shorted-anode field-stop trench IGBT (FS SA T IGBT) is the intermittent insertion of the n^+ collector in the p^+ collector layer. In this case, the n^+ collector directly contacts the field-stop layer and acts as a cathode of the PN diode, while the p^+ collector layer acts as the general collector of FS T IGBT. This SA IGBT has an enhanced current capability with the same package and improves cost structure because a co-packaged anti-parallel diode is not required and the bigger die can be loaded on the package.

Even though FRD and IGBT functions are combined, the FS SA T IGBT performs better than conventional FS T IGBTs.



(a) $V_{CE(sat)}$ Comparison



(b) Saturation Current Comparison

Figure 3. Saturation Voltage vs. Collector Current

Figure 3 illustrates comparison between a new device (FGA30S120P) and a conventional FS T IGBT (FGA30N120FTD) in terms of the saturation voltage and current characteristics. The two devices have the same current rating. At the rated current, 30 A; $V_{CE(sat)}$ of FGA30S120P is 1.71 V, while that of FGA30N120FTD is 1.96 V (12.8% improved). The saturation current of the new device is more than twice that of the previous one.

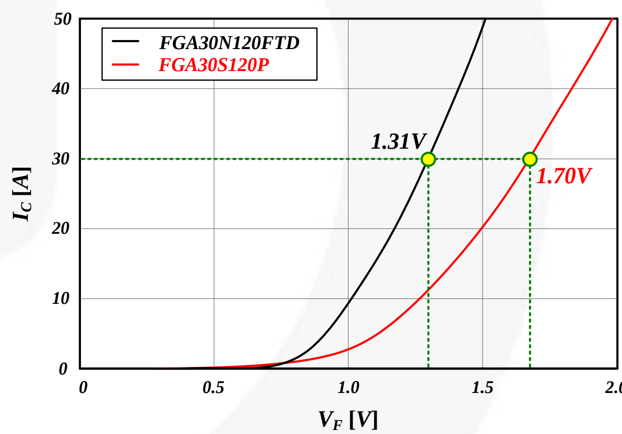


Figure 4. Forward Voltage Drop Comparison

Figure 4 shows the forward voltage drop characteristics of the anti-parallel diode of FGA30S120P and FGA30N120FTD. At the rated current, 30 A; the forward voltage drop, V_F, of FGA30S120P is 1.70 V, while that of FGA30N120FTD is 1.31 V. Since new device utilizes a p base and a lightly doped n^- drift layer of IGBT structure as a FRD; while the conventional IGBT is co-packaged with a UFRD, the forward voltage drop of body diode is inevitably higher than the conventional.

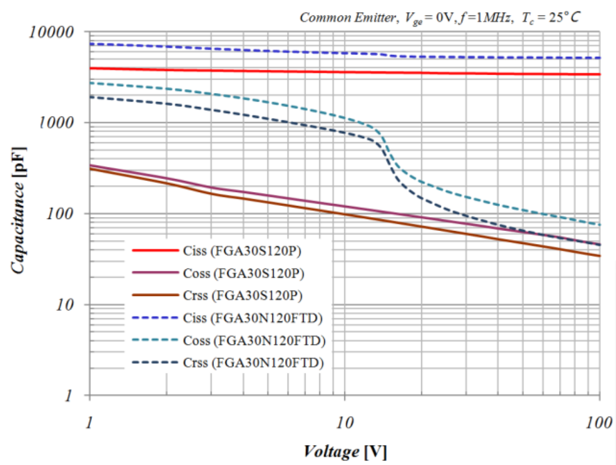


Figure 5. Capacitance Comparisons

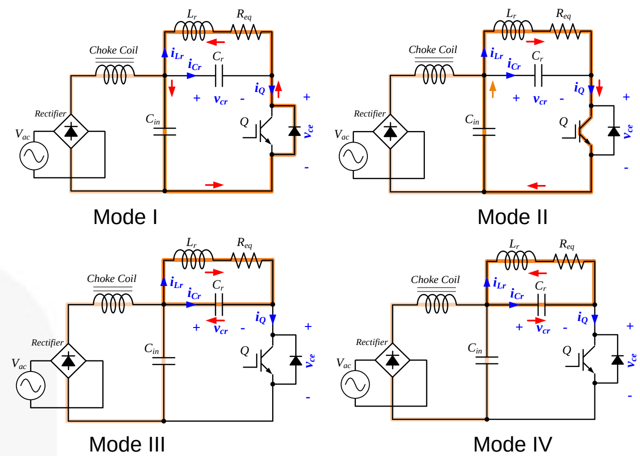
Figure 5 shows the capacitance characteristic comparison between FGA30S120P and FGA30N120FTD. Through an advanced trench gate and optimized field-stop layer structures, lower capacitance characteristics and lower gate charge were achieved in the new device, FGA30S120P, so better switching performances are expected.

SE Resonant Inverter for IH Applications

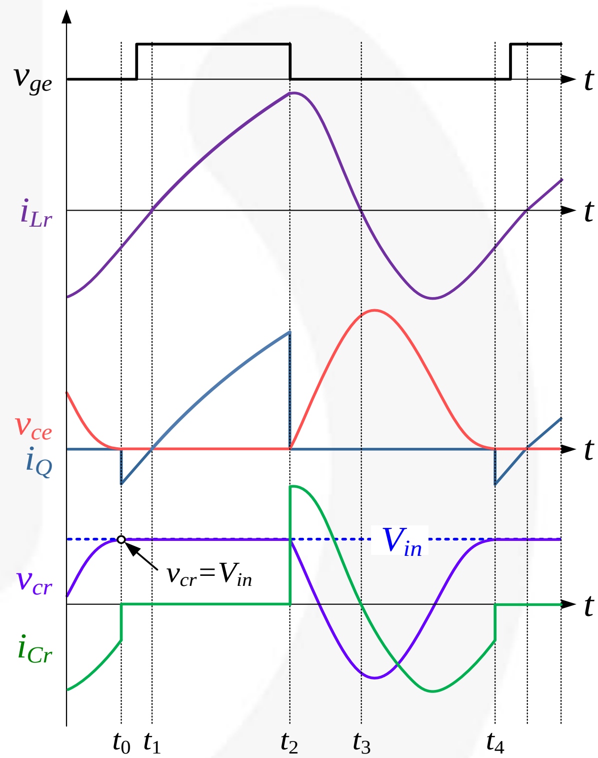
The SE resonant inverter is a type of class "E" series resonant inverter popularly used in IH applications due to its lower cost structure and relatively high efficiency.[1-4] The basic operation modes and the theoretical waveforms of are illustrated in Figure 6. The rectifier, the choke coil, and the input capacitor (C_{in}) compose a low-pass filter (LPF). The working coil can be equivalently considered as the series of inductance (L_r) and resistance (R_{eq}) that composes the resonant tank with the capacitor (C_r).

The operation of inverter is divided into four modes, as shown in Figure 6(a). During Mode I (the period from t_0 to t_1), the resonant current flows through the anti-parallel diode, thus the collector-emitter voltage (V_{CE}) of the IGBT, Q, becomes zero. The IGBT should be turned on within this mode to achieve zero voltage switching (ZVS). During Mode II (the period from t_1 to t_2), the inductor current flows through the IGBT. The IGBT is turned-off at the t_2 instant and Mode III begins. A quasi-resonance circuit between L_r and C_r is formed in this mode. At t_3 instant, the direction of the resonant current changes and Mode IV begins. At t_4 instant, the resonant voltage becomes zero and next four modes are repeated.

The IGBT in the SE resonant inverter is turned on under the ZVS condition by the freewheeling current and turned off under the quasi-ZVS condition using a voltage resonance much higher than input voltage. To turn on the IGBT under ZVS condition, the anti-parallel diode is required, even though it only commutates for a short period. During the off period, the voltage resonance between L_r and C_r occurs, requiring much higher breakdown voltage of IGBT. Generally, 1000~1600 V IGBTs are used in SE resonant inverter applications.



(a) Circuit Diagrams and Operation Modes



(b) Theoretical waveforms

Figure 6. SE Resonant Inverter for IH Application

To achieve ZVS turn-on and turn-off, the off-time must be fixed to the same as t_2~t_4 period, while the on-time is variable to control the power.

Through the ZVS operation, this inverter can provide high efficiency. However, a high-voltage IGBT is needed as a switching device because very high resonant voltage is applied to the IGBT. Techniques suppressing the switching voltage stress by an auxiliary additional IGBT and clamping circuit have been proposed[5,6], but they are not practical for real IH applications due to the high cost. Therefore, the conventional SE resonant inverter continues to gain popularity, especially in IH cookers, rice jars, and inverterized microwave ovens.

Both $V_{CE(sat)}$ and the tail current of IGBT are key factors determining the system efficiency and ensuring the stability in IH applications.

Even though an IGBT is a suitable switching device for high-voltage applications, both $V_{CE(sat)}$ and the tail current should be increased if its breakdown voltage is increased.

In the SE resonant inverter in Figure 6, i_{Leq} flows through L_{eq}, R_{eq}, Q and C_{in}; and the energy is transferred to the load during the IGBT-on period. Thereby the voltage equation is:

$$V_{in} - L_{eq}\frac{di_{Leq}}{dt} - R_{eq}i_{Leq} = 0 \qquad (1)$$

The inductor current is derived as:

$$i_{Leq(on)}(t) = \frac{E}{R}\left(1 - e^{-\frac{R}{L}t}\right) \qquad (2)$$

When IGBT Q is turned off at t_2, the resonance between L_r and C_r begins and the voltage and current equations are derived as:

$$\frac{V_{in}}{s} - \frac{1}{sC}I_{off}(s) + L\{sI_{off}(s) - I_o\} + RI_{off}(s) = 0 \qquad (3)$$

$$i_{Leq(off)}(t) = e^{-\alpha t}A\cos(\omega t + \theta) \qquad (4)$$

where,

$$A = \sqrt{\left(\frac{E}{\omega L} - \frac{\alpha I_o}{\omega}\right)^2 + I_O^2}, \qquad \theta = \tan^{-1}\left(\frac{\alpha L I_O - E}{\omega L I_O}\right)$$

$$\alpha = \frac{R_{eq}}{2L} \quad \text{and,} \quad \omega = \sqrt{\frac{1}{LC} - \left(\frac{R_{eq}}{2L}\right)^2}$$

To turn on an IGBT under ZVS condition, an anti-parallel diode is required; however, the diode only commutates for a short period – its performance is insignificant.

Experimental Results

To verify the validity of the new FS SA T IGBT in SE resonant inverter for IH applications, an experiment with a 1.8 kW single-ended resonant inverter in an IH cooker was designed and tested.

Figure 7 shows the measured waveforms of the gate signal and the switching voltage and current of the experimental test set-up. As displayed, the IGBT is turned on and turned off under the zero-voltage condition. Figure 7 also shows that the amount of the diode current is much smaller than IGBT current, which illustrates the new FS SA T IGBT is a suitable switching device in the single-ended resonant inverter despite its inferior intrinsic diode performance. The switching performance comparison is illustrated in Figure 8. The result shows that the new device is a little inferior to the previous version in terms of the turn-off transient – the turn-off energy (E_{off}) of FGA30S120P is 160 μJ, while that of FGA30N120FTD is 141 μJ.

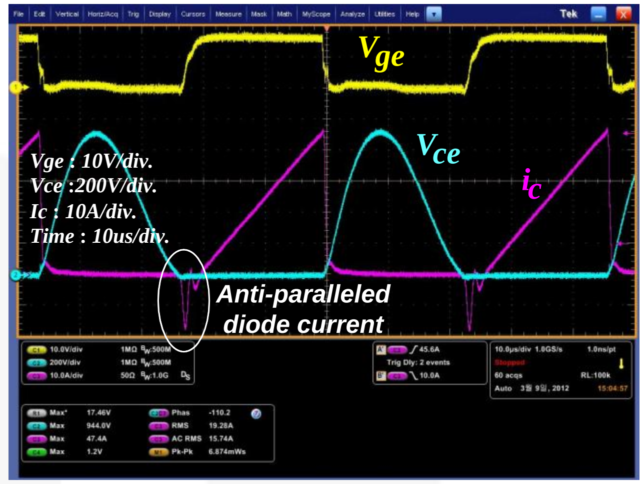


Figure 7. Operation Waveforms

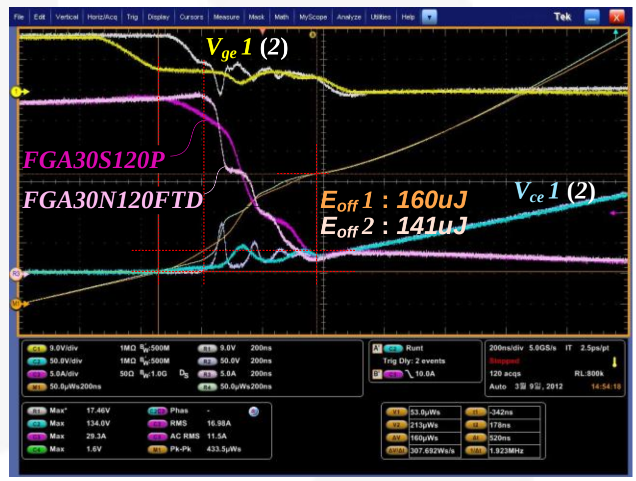


Figure 8. Switching Performance Comparison

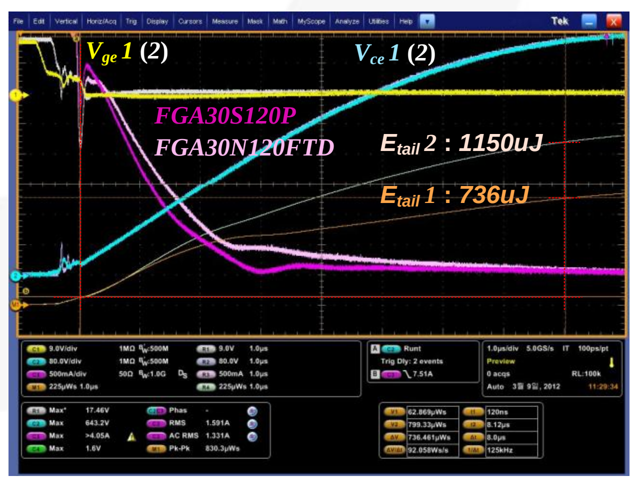
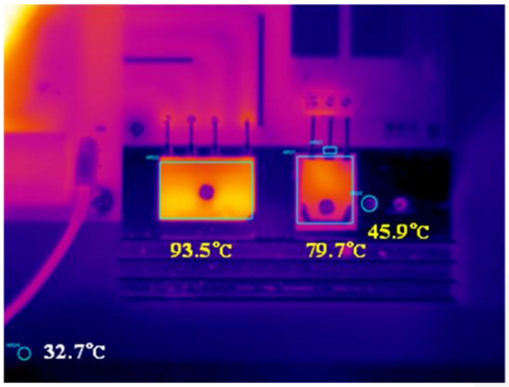
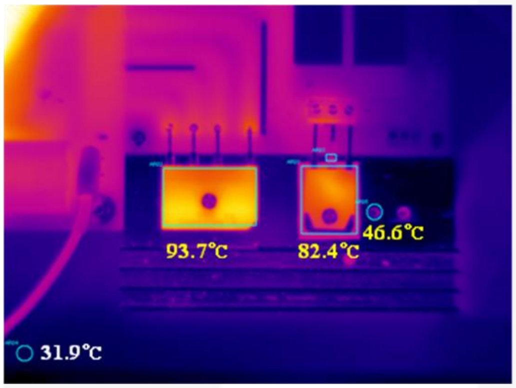


Figure 9. Tail Current Loss Comparison



(a) FGA30S120P



(b) FGA30N120FTD

Figure 10. Thermal Performance Comparison

From the standpoint of the tail current loss, the new device is superior to the previous version. Figure 9 illustrates the tail current loss comparison. The tail current loss of FGA30S120P is 736 µJ, while that of FGA30N120FTD is 1150 µJ. As a result, the new device can significantly reduce the total loss because of its lower $V_{CE(sat)}$ and much smaller tail current, despite slightly slower turn-off transition.

Figure 10 shows the thermal performance comparison results. At the maximum power, 1.8 kW, the measured case temperature of FGA30S120P is 79.7°C. That of the FGA30N120FTD is 82.4°C. Even though the new device includes intrinsic body diode, it shows better thermal performance in comparison to the previous device.

Conclusion

New field stop shorted anode trench IGBT products, FS SA T IGBT that embed the intrinsic body diode like MOSFET, have been introduced and their validity in the single-ended resonant inverter for induction heating application is described in this application note. Even though both FRD and IGBT functions are combined into single chip, Fairchild’s shorted-anode silicon technology offers lower saturation voltage, up to 12.5%, and lower tail current, up to 36 %, than the same rating NPT trench IGBT.

References

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[6] D-Y Lee, and D-S Hyun, “A New Hybrid Control Scheme using Active-Clamped Class-E Inverter with Induction Heating Jar for High-Power Applications,” *Journal of Power Electronics*, Vol. 2, No. 2, pp. 104-111, April 2002.
[7] J-E Yeon, M-Y Park, K-M Cho, H-J Kim; “Field-Stop Shorted-Anode Trench IGBT for Induction Heating Appliances,” IECON 2012, pp. 422 – 426.

Appendix — Field-Stop Shorted-Anode Trench IGBTs

Part Number	Built-in Diode	BVCES (Min.) [V]	Fall Time (ns @ 175°C) [ns]	IC (Max.) (A @ 100°C)	$R\Theta_{JC}$ (°C/W)	$V_{CE(sat)}$ (Typ.) [V]	$V_{GE(th)}$ (Min.) [V]	Package	Generation
FGA50S110P[1]	Yes	1100	TBD	TBD	TBD	TBD	TBD	TO-3P 3L	Second
FGA15S125P	Yes	1250	250	15 A @ 100°C	1.10	2.25	4.5	TO-3P 3L	Second
FGA20S120M	Yes	1200	520	20 A @ 100°C	0.43	1.55	4.5	TO-3P 3L	First
FGA20S125P	Yes	1250	250	20 A @ 100°C	0.60	2.00	4.5	TO-3P 3L	Second
FGA25S125P	Yes	1250	232	25 A @ 100°C	0.60	1.75	4.5	TO-3P 3L	Second
FGH30S130P	Yes	1300	270	30 A @ 100°C	0.30	1.75	4.5	TO-3P 3L	Second
FGA30S120P	Yes	1300	270	30 A @ 100°C	0.43	1.75	4.5	TO-3P 3L	Second
FGA20S140P	Yes	1400	356	20 A @ 100°C	0.55	1.90	4.5	TO-3P 3L	Second

Note:
1. In development; not released to production.

Related Datasheets

FGA15S125P — 1250 V, 15 A Shorted Anode IGBT

FGA20S125P — 1250 V, 20 A Shorted Anode IGBT

FGA25S125P — 1250 V, 25 A Shorted Anode IGBT

FGA30S120P — 1300 V, 30 A Shorted Anode IGBT

FGH30S130P — 1300 V, 30 A Shorted Anode IGBT

FGA20S140P — 1400 V, 20 A Shorted Anode IGBT

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