Next Generation 1.7 kV Chipset: Fine-Pattern Trench IGBT and Ultra-Thin FSA Diode for Traction Applications

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The Power Point Presentation will be available after the conference.

Abstract

A fine pattern (distance between trenches < 2 µm) trench gate IGBT technology and an ultra-thin (< 200 µm) FSA diode have been developed at Hitachi Energy for implementation in the next generation 1.7 kV chipset. This paper describes the design and technology upgrades enabling an improved performance whilst maintaining high ruggedness in terms of reverse biased safe operating area and short circuit capability. Compared to the previous generation chipset, the fine pattern trench gate IGBT shows a reduction of 23% in saturation voltage at the same current density and switching loss, while the new ultra-thin FSA diode exhibits a reduction in leakage density of 7% and a reduction of 55% in reverse recovery energy at the same current density and switching speed.

1 Introduction

Development of power semiconductor devices is driven by increasing customer needs, such as output power, safe operating area (SOA), long term reliability and operating temperature range. Specific applications require a further optimization in performance that must be properly addressed by fine tuning and incremental improvements of an established product or the development of a new technology platform. In particular, traction applications typically entail specific requirements such as the capability of withstanding a short circuit (SC) pulse duration of at least 10 µs and a loss profile optimized for high frequency operation.

In this work, we introduce and discuss the development of a new technology platform to be implemented in our next generation 1.7 kV chipset optimized for traction applications. The new technology is based on a fine pattern trench gate IGBT and an ultra-thin field shielded anode (FSA) diode. Three representative IGBTs with different design parameters such as the silicon thickness and/or the anode injection efficiency have been thoroughly characterized and used to drive the new FSA diode.

The performance of the new chipset has been compared with the one of the previous generation chipset. Tested at the same current density and switching speed, the IGBT shows a reduction of 23% in saturation voltage and the diode exhibits a reduction of 55% in reverse recovery energy, still ensuring ruggedness and suitability for 175°C junction operating temperature.

2 IGBT design

Figure 1 shows a schematic diagram of the new fine pattern (FP) trench 1.7 kV IGBT.

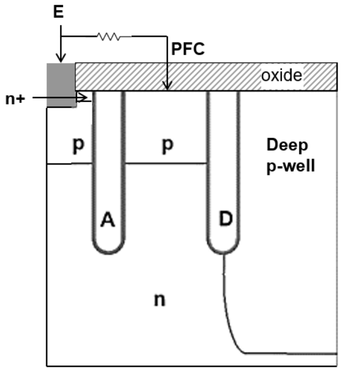

Fig. 1 Schematic diagram of the new 1.7 kV FP trench IGBT (half-cell). A: active trench (gate-biased). D: dummy trench (emitter-biased).

The new IGBT is based on an optimization of a newly developed low voltage trench IGBT technology platform [1, 2], adapted to work at a higher voltage rating thanks to a redesigned termination and a different silicon thickness and resistivity.

As it will be shown in more detail in the electrical characterization section, the new IGBT provides a significant performance improvement with respect to the enhanced planar cell (SPT++) used in previous IGBT generations. This is achieved thanks to the combination of a deep p-well, a dummy trench closely spaced to the active trench and the plasma flow control (PFC) feature [1, 2]. In particular, the deep p-well and the dummy trench protect the active trench from dynamic avalanche ensuring long term reliability, the dummy trenches reduce the Miller capacitance C_{gc} reducing the IGBT switching losses, and an optimized PFC design allows, depending on the application, to obtain the right trade-off between static losses, switching losses, turn-on controllability and short circuit oscillations.

3 Diode design

The new diode is based on the field shielded anode (FSA) concept [3], in which low leakage currents are obtained by placing the frontside irradiation peak away from the high electric field region formed in the blocking state.

Figure 2 summarizes the design modifications implemented in the new diode to improve the previous generation of the FSA diode.

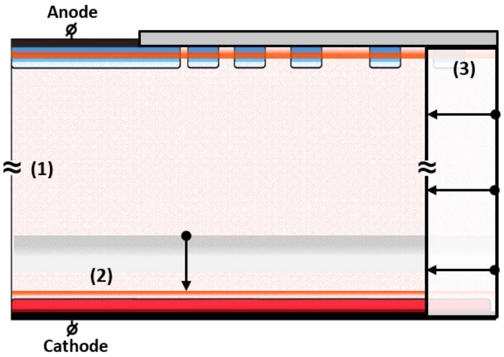

Fig. 2 Schematic diagram of the FSA diode with improvements: (1) thin diode body for reduced losses, (2) ultra-shallow buffer and (3) optimized termination.

By employing an ultra-thin (< 200 µm) diode body in combination with an optimized shallow cathode buffer, the new design achieves extremely low leakage currents suitable for operation at 175°C, low static and dynamic losses while retaining a positive temperature coefficient that is ideal for parallel operation.

Moreover, a narrower, optimized termination and resistive zone provide more space for the active area and ensure robustness at even higher current densities than previously achieved.

Figure 3 shows a schematic comparison of the electric field and the doping profile of the previous generation and a new FSA diode with a shallow buffer.

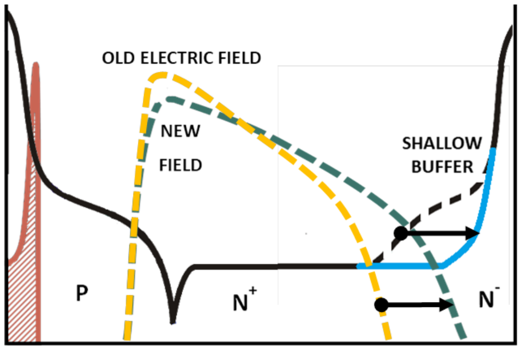

Fig. 3 Vertical cut showing the doping profiles, irradiation peak and electric field shape while in the blocking state, illustrating the effect of the ultra-shallow buffer on the field.

The reduced buffer depth leads to more space for the electric field to expand in the blocking state; thus, keeping constant the silicon thickness a lower electric field peak at the junction between the anode and the silicon body is obtained. In the new FSA diode this margin allowed for the reduction in silicon thickness while still ensuring blocking capability and softness.

Depending on application requirements, the new design can be combined with a backside proton peak to enhance the diode softness at the cost of some degradation of the leakage current [4].

4 Electrical characterization

4.1 Devices and methods

The new 1.7 kV chipset technology has been assessed using three IGBT design variations (A, B, C, see Table 1) with different combinations of silicon thickness and anode injection efficiency.

The electrical characterization has been performed using a test vehicle with more chips in parallel, contributing to a nominal current I_{nom} = 750 A.

IGBT	Silicon thickness	Anode injection efficiency
A	Low	Low
B	Low	High
C	High	Low

Table 1 Summary of the IGBT design variations

4.2 IGBT performance

Figure 4 shows the technology trade-off curve for the new IGBT variations included in this study, compared with the SPT++ IGBT. The improvement achieved by the new technology is clear, showing the possibility to achieve a 23% reduction in collector-emitter saturation voltage V_{cesat} for the same turn-off switching energy E_{off}.

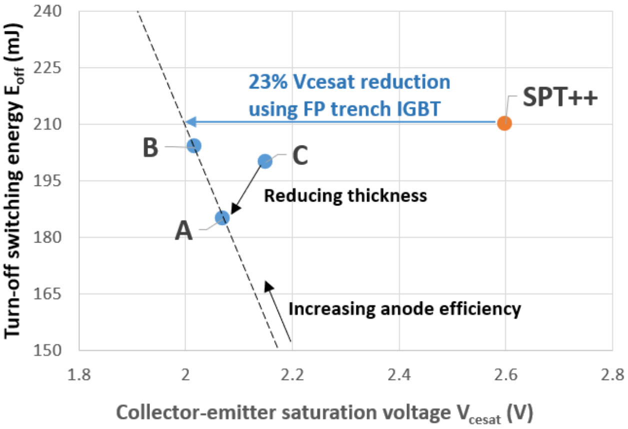

Fig. 4 Technology trade-off curve at 25°C comparing the new 1.7 kV FP IGBTs with the SPT++ IGBT at the same current density and switching conditions.

Figure 5 shows the IGBT turn-off characteristics measured at nominal conditions and operating junction temperature T_{vj} = 150°C. As clearly visible in the technology trade-off curve of Fig. 4, the thicker (device C) and the higher anode injection efficiency (device B) IGBTs have slightly higher switching losses than the reference device A.

This is directly related to a higher plasma concentration to be depleted during turn-off, as demonstrated by the longer tail current in Fig. 5 for devices B and C.

All the devices show good ruggedness in terms of reverse bias safe operating area (RBSOA) and short circuit capability, as detailed in the following.

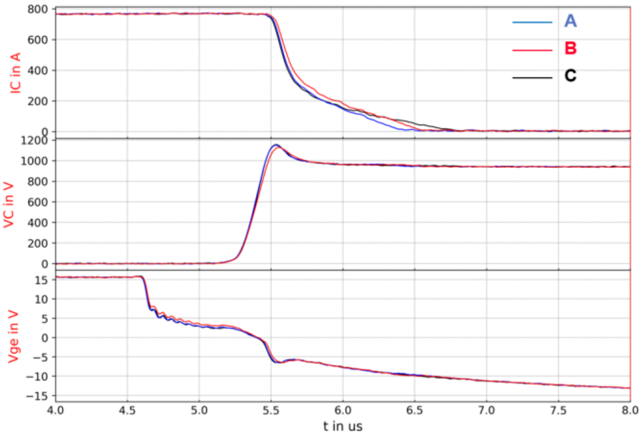

Fig. 5 IGBT turn-off, nominal (V_{cc} = 900 V, I_c = 750 A); $R_{g\text{-}off}$ = 4.7 Ω; L_σ = 80 nH; T_{vj} = 150°C.

Figure 6 shows the RBSOA waveforms for the three design variations. All tested devices can be switched at RBSOA voltage (V_{cc} = 1300 V) and 3x the nominal current.

The effect of the silicon thickness on the RBSOA waveforms is clear as the thicker device C shows reduced dynamic avalanche compared to A and B.

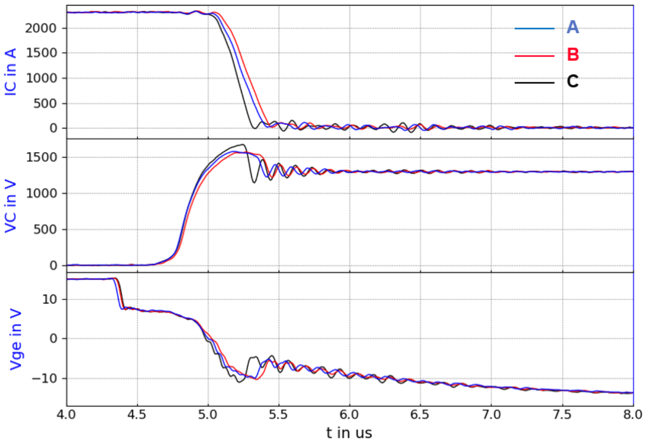

Fig. 6 RBSOA waveforms (V_{cc} = 1300 V, I_c = 3xI_{nom} = 2250 A); $R_{g\text{-}off}$ = 5 Ω; Ls = 44 nH; T_j = 25°C.

Figure 7 shows the short circuit waveforms for the three IGBTs. Devices A and B show a very similar behavior and the same SC capability, as they are able to withstand a short circuit pulse duration t_p of 10 µs at T_{vj} = 150°C. Device B shows slightly higher SC current due to a stronger anode injection efficiency vs. device A. However this does not translate into lower SC capability, as the corresponding increase in power consumption during the pulse is negligeable.

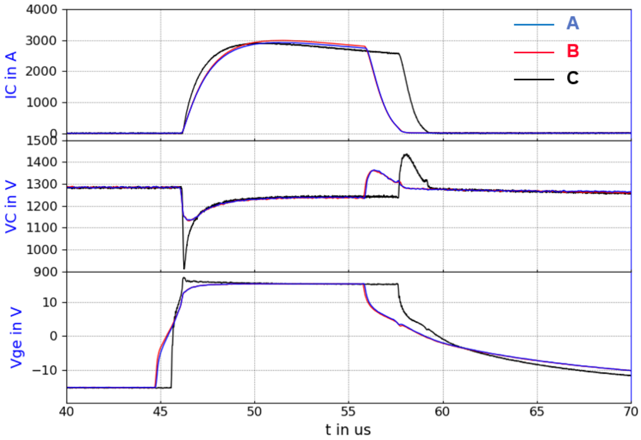

Fig. 7 SC waveforms; V_{cc} = 1300 V, V_{ge} = 15 V, $t_p \geq 10$ µs; $R_{g\text{-}on} \leq 3.3$ Ω; L_σ = 80 nH; T_{vj} = 150°C.

The higher silicon thickness of device C translates into an improvement in SC capability. In particular, device C can withstand a t_p of 12 µs. The capability is not limited by the switching speed, as $R_{g\text{-}on}$ values as low as 1 Ω were used for this test. Considering also the reduced dynamic avalanche previously observed in Fig. 6 for device C, we can conclude that the thickness variation range studied here enables a clear trade-off between performance and ruggedness.

4.3 Diode performance

A representative diode based on the new ultra-thin FSA technology has been characterized using the three IGBT devices described in the previous section. Figure 8 shows the turn-off transient of the diode in nominal conditions tested with each of the proposed IGBT designs: the diode maintains similar dynamic behavior for each IGBT.

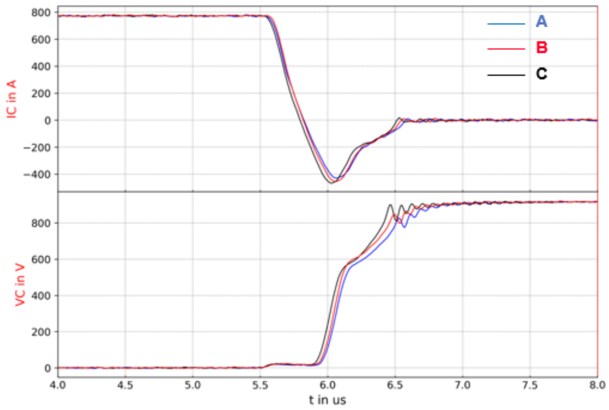

Fig. 8 Diode turn-off, nominal (V_{cc} = 900 V, I_c = 750 A); $R_{g\text{-}on}$ = 1.2 Ω; L_σ = 80 nH; T_{vj} = 150°C.

Figure 9 exhibits a direct comparison of the reverse recovery energy at DC-link voltage (V_{cc} = 900 V) for the new ultra-thin FSA diode and the previous generation device.

In order to ensure a fair comparison, both devices have been tested at the same current density levels and at the same switching speed, using the IGBT device C.

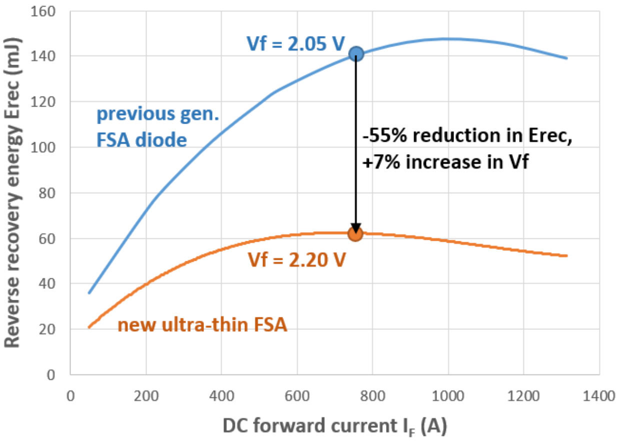

Fig. 9 Reduction in reverse recovery energy (T_{vj} = 150 °C) enabled by the new ultra-thin FSA diode. Switching conditions as in Fig. 8. IGBT: device C.

The new ultra-thin FSA diode offers a substantial advantage in terms of switching losses; in particular, the diode design included in this study achieves in nominal switching conditions (I_{nom} = 750 A) a reduction of 55% in reverse recovery energy E_{rec} at the cost of a slight increase (+7%) in forward voltage V_f.

Depending on the specific requirements from the application, the diode design can be modified to reduce V_f, for instance increasing the anode injection efficiency or reducing the irradiation dose, matching or improving the previous technology diode in terms of static loss while keeping margins in switching loss.

As summarized in the design section, one of the main factors in the technology improvement for the diode was the reduction in silicon thickness. Potential risks and limitations in reducing the silicon thickness for the diode consist in the softness and blocking capability, due to the high fields formed while in the blocking state or during turn-off.

To assess these potential limitations, the blocking capability was verified and the diode softness limits were studied at harsh conditions, i.e. by turning off the diode at low temperature (T_{vj} = 25°C), SOA voltage (V_{cc} = 1300 V), gradually reducing the current levels and increasing the switching speed (i.e. reducing the gate resistance $R_{g\text{-}on}$).

Figure 10 shows that even in the harshest conditions ($I_c = 0.1 x I_{nom}$, $R_{g\text{-}on}$ = 1.2 Ω), the new FSA diode is soft enough, as the overvoltage is well below 1700 V.

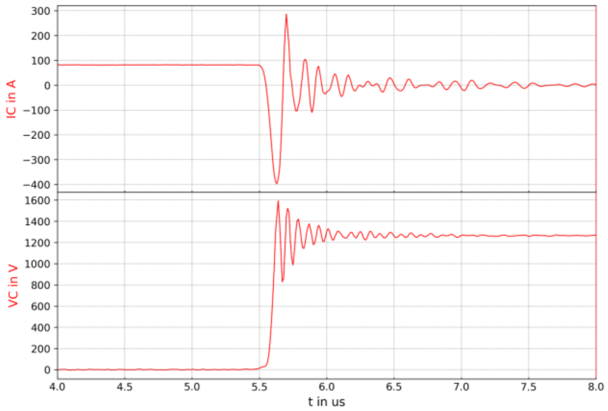

Fig. 10 Diode softness (V_{cc} = 1300 V, I_c = 0.1x I_{nom} = 75 A); $R_{g\text{-}on}$ = 1.2 Ω; L_σ = 80 nH; T_{vj} = 25°C. IGBT: design B.

The softness margin has been achieved despite the ultra-low thickness of the silicon body thanks to a careful optimization of the shallow cathode buffer profile.

The engineering of the cathode buffer was also instrumental in keeping the leakage current low enough to ensure operation at T_{vj} = 175°C. In particular, the leakage current was measured at T_{vj} = 175°C, V_{cc} = 1700 V and sampled at t = 100 ms for both the previous and the new diode technology, resulting in an improvement of 7% in leakage current density.

5 Conclusion

A fine pattern trench gate IGBT technology and an ultra-thin FSA diode have been developed at Hitachi Energy for implementation in the next generation 1.7 kV chipset. The new fine pattern trench gate IGBT shows a reduction of 23% in saturation voltage at the same current density and switching loss, while the new ultra-thin FSA diode exhibits a reduction in leakage density of 7% at T = 175°C and a reduction of 55% in reverse recovery energy at the same current density and switching speed. The improved performance has been achieved while keeping good ruggedness in terms of RBSOA, SCSOA and diode softness capability.

6 Reference

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