A new sub-micron trench cell concept in ultrathin wafer technology for next Generation 1200 V IGBTs

Christian Jaeger, Alexander Philippou, Antonio Vellei*, Johannes G. Laven, Andreas Härtl
Infineon Technologies AG, Munich, Germany, christian.jaeger@infineon.com
*Infineon Technologies Austria AG, Villach, Austria

***Abstract*— The overall growing trend towards electrification and, at the same time, the urgent need to minimize energy consumption strongly requires higher energy efficiency in power electronics. We present a new technology concept for next generation 1200 V IGBTs with vastly reduced overall power losses using an optimized micro-pattern trench (MPT) cell design with sub-micron mesas. Further important parameters relevant for inverters driving electrical machines were optimized, including turn-off softness, dv/dt-controllability, and short circuit capability, providing a right-fit solution to customer requirements.**

Keywords—micro-pattern trench; narrow mesas; drives applications.

I. Introduction

A huge step towards higher current densities for insulated gate bipolar transistors (IGBTs) was the change from planar-gate to trench-gate configuration [1]. The trench-IGBT concept, which originally used a square trench profile (top view see Figure 1 a), allows using the vertical direction for electron channel formation resulting in an increased channel width and an improved overall performance.

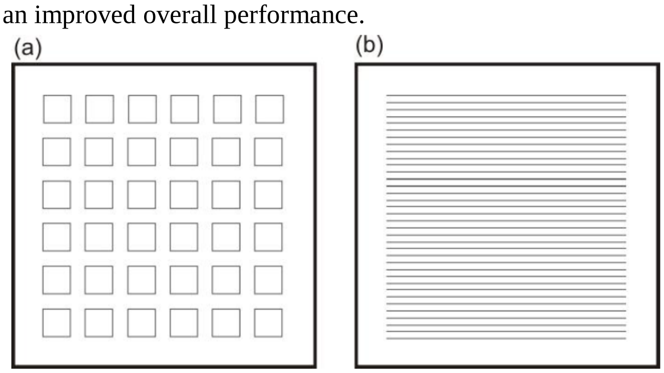

Fig. 1: Sketches of (a) squared trench cell and (b) micro pattern trench (MPT) stripe cell in top view showing the trenches on the chip.

Further increase of the channel width of IGBTs can be reached by narrow parallel trenches separated by sub-micron mesas (top view Figure 1 b). This so-called micro-pattern trench IGBT (MPT-IGBT) (see Fig. 2 a) has an enormous benefit for applications requiring no short-circuit withstand capability, since a higher channel width directly lowers the on-state voltage drop [2], [3].
Also for applications requiring a certain short-circuit withstand time (typically at least 6-8 µs for drives applications), the MPT-IGBT shows considerable performance improvement [4]. However, the channel width of the micro-pattern trench (MPT)-IGBT has to be adjusted in that case.
We present a new technology concept for next generation 1200V IGBTs using the MPT concept optimized for drives applications. In addition to channel width optimization, the cell design was adapted to the best trade-off between turn-on losses and voltage slope (dv/dt) at low currents, which is typically restricted to below 5 kV/µs for inverters driving electrical machines due to motor windings lifetime. Furthermore, an optimized vertical structure and leading edge ultrathin wafer technology (down to 100 µm Si thickness) were used [5].

II. Overall device concept

A. Cell concept

In addition to the higher channel width, the use of MPT cell structures with sub-micron mesas (see Fig. 2 a) enables a

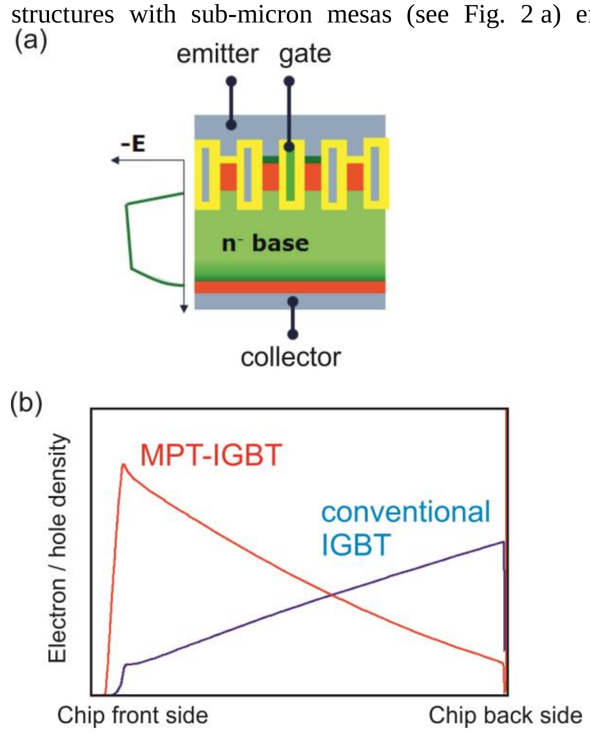

Fig. 2: (a) New generation 1200 V IGBT micro-pattern trench cell with parallel sub-micron mesas at the chip front side. (b) Comparison of carrier density within the devices for conventional IGBTs and micro-pattern trench (MPTs) IGBTs.

considerably higher carrier confinement during on-state at the chip front side compared to a conventional square cell (see Fig. 2 b), resulting in drastically lower conduction losses [6]. Furthermore, the vertical charge carrier profile realized by the MPT cell allows removing a large portion of the charge carriers from the device during turn-off while the voltage drop over the device is still low. This results in an overall improved $V_{CE,sat}$ versus E_{off} trade-off for MPT cell structures.
In general, the MPT-IGBT has a huge parameter space to tune the channel width, capacitances, and carrier confinement by design. This proves an enormous benefit for fine-tuning the device performance to modern application requirements.
Some possible building blocks for cell structure optimization are shown in Fig. 3 including 'active gates', 'source trenches' and 'dummy gates'. While 'active gates' have contacts and n-source regions next to the gate trenches, 'dummy gates' yield no electrical contacts to the channel regions and can thus only passively influence the device characteristics by balancing the Gate-to-Drain and Gate-to-Source capacitances of the device.

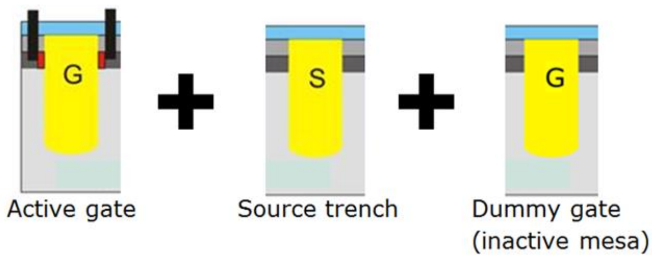

Fig. 3: Possible building blocks for cell structure optimization for MPT-IGBTs.

With the optimal arrangement of these building blocks, the channel width can be adapted to ensure sufficient short circuit withstand time of the devices. Furthermore, the trade-off between voltage slopes (dv/dt) and switching losses can be optimized. The adaption of the available n-source area on the chip surface is an additional degree of freedom for adjusting the saturation current [4].

B. *Vertical design*

It is commonly known that a prominent device parameter resulting in a break of the typical trade-off between switching and conduction losses is the chip thickness, hence by reducing the chip thickness both switching and conduction losses are minimized. To be able to achieve sufficient breakdown voltage for lower chip thicknesses a lower base material doping in combination with an optimized field-stop design is used. The lower base material doping results in a smoother electric field distribution and a higher breakdown voltage (see Fig. 4). To obtain a soft turn-off of the device a careful optimization of the field-stop design is required [7].

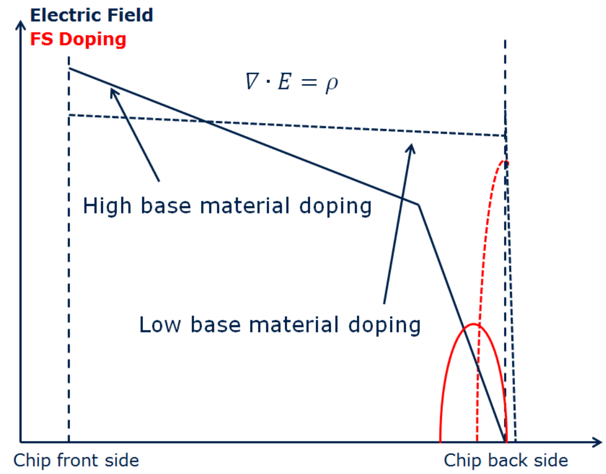

Fig. 4: Schematics of electric fiel distribution for high (blue, full line) and low (blue, dashed line) base material doping. The corresponding sketches of FS doping are also added (red lines).

III. Results

A. *Device performance*

The trade-off between $V_{CE,sat}$ and E_{off} for the MPT cell structure compared to a conventional 1200 V IGBT (Fig. 5) shows a considerable reduction of the $V_{CE,sat}$ by up to ~600mV at constant E_{off}. As already mentioned, the vertical charge carrier profile realized by the MPT cell results in an overall improved $V_{CE,sat}$ versus E_{off} trade-off.
Especially for inverters driving electrical machines, where the voltage slope (dv/dt) is typically limited to below 5 kV/µs, turn-on losses have to be optimized also in the limit of small voltage slopes. Typically, the voltage slope is highest at low currents (e.g., at 1/10 nominal current) and low temperatures (e.g., 25 °C), while power losses dominate at high values of current and temperature. The turn-on losses of the MPT cell were reduced by optimal arrangement of different trench potentials using the building blocks shown in Fig. 3. For the optimized MPT cell, the trade-off between E_{on} and the voltage slope improved compared to previous IGBT generation (Fig. 6). At a fixed voltage slope of, e.g., 5 kV/µs a reduction of E_{on}/A by ~10% was achieved.

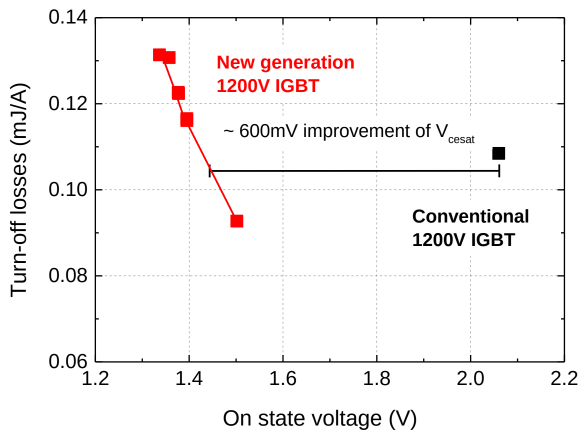

Fig. 5: Output characteristics of new generation 1200 V IGBTs compared to conventional IGBTs.

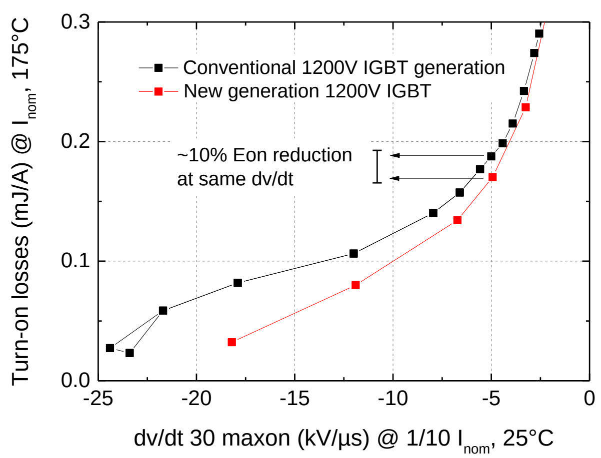

Fig. 6: Comparison of Eon (Inom, T=175°C) versus dv/dt (1/10 Inom, T=25°C) for new generation 1200V IGBTs and conventional IGBTs.

B. *Softness and device robustness*

In addition to the above mentioned performance improvement, the MPT-IGBT is able to maintain the turn-off softness and short-circuit ruggedness. Figure 7 shows turn-off waveforms for the new MPT IGBT compared to a conventional IGBT for different DC-Link voltages. For the measurements shown here intentionally an external stray inductance of 500 nH was added to the measurement setup to provoke softness oscillations. The turn-off of the MPT-IGBT is slightly smoother despite the lower losses, which enables its use for hard-switching applications.

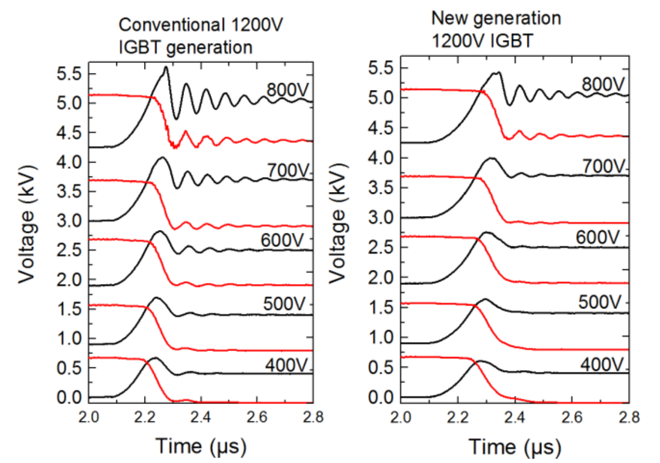

Fig. 7: Turn-off waveforms for conventional 1200 V IGBT generation (left) and new generation 1200 V IGBTs (right) for different DC-link voltages (black: voltage, red: current). External stray inductance of 500 nH was used to provoke oscillations of the IGBTs (no typical use conditions shown here).

Also a sufficient short-circuit capability is ensured for the new generation 1200 V IGBTs, as can be seen in Fig. 8. A thermal short-circuit withstand-time of more than 8µs at 150 °C was reached which is sufficient for standard drives applications.

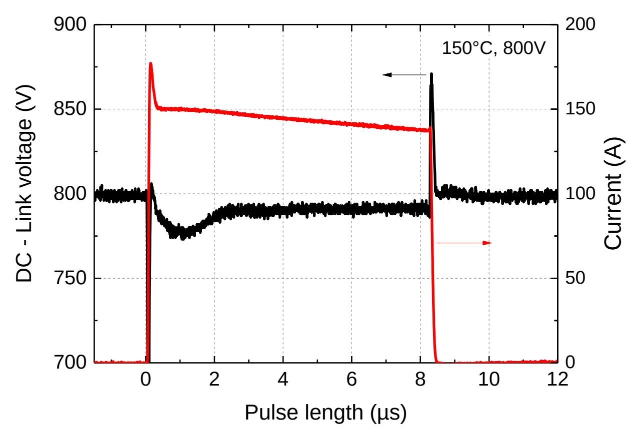

Fig. 8: Thermal short-circuit event for new generation 1200 V IGBT (red: current, black: voltage). A short-circuit withstand-time of 8 µs at 150 °C was reached.

The impact of base material doping and device thickness on the breakdown voltage is shown in Fig. 9. For lower base material doping levels (green and purple) higher blocking voltages are reached, i.e., for a reduced silicon thickness (90%) and a lower base material doping level (60%) (purple curve), the same breakdown voltage can be reached as for the standard silicon thickness and base material doping (100%) (blue curve).

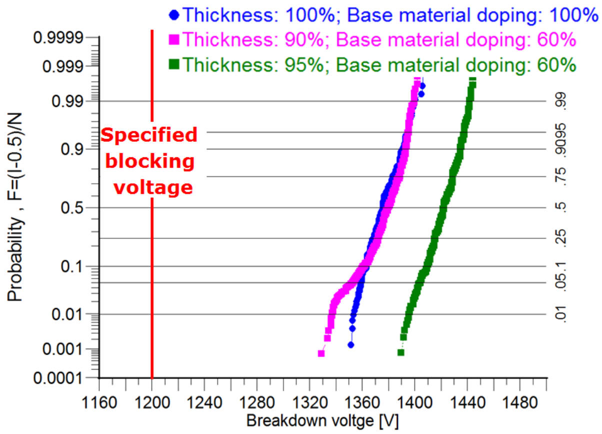

Fig. 9: Cummulative frequency plot of breakdown voltage distribution for different silicon thicknesses and base material doping.

C. *Performance demonstration*

To demonstrate the enormous $V_{CE,sat}$ improvement of MPT-IGBTs (compare Fig. 5), a special test module was built up with conventional IGBTs and MPT-IGBTs placed in series configuration (details see Fig. 10). This setup ensures that the same DC current flows through both new and conventional IGBTs, which results in a resistive heating of the devices depending on the respective on-state voltage drop. The lower Joule heating for MPT-IGBTs caused by the lower $V_{CE,sat}$ consequently results in a lower local heating. For visualization the modules interior and the IGBTs were painted black and monitored by a thermo-camera. The resulting image shows that the device temperature due to conduction losses is considerably lower by about 20 °C for the novel MPT-IGBTs compared to conventional IGBTs at the same current flow (Fig. 11).

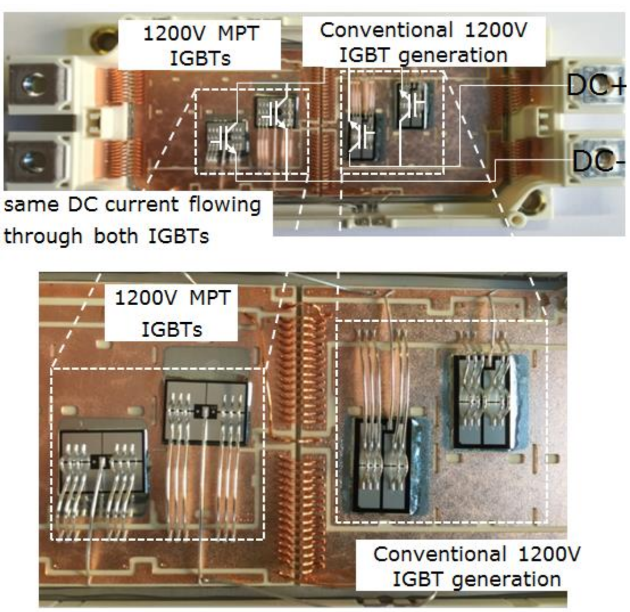

Fig. 10: Setup for demonstration of low conduction losses by means of thermo camera measurements.

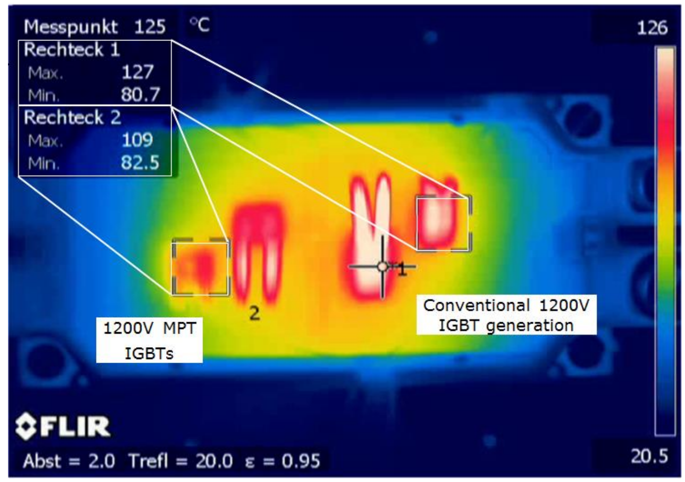

Fig. 11: Thermo camera images demonstrating low conduction losses of MPT-IGBTs.

IV. Conclusion

We presented a new technology concept for next generation 1200 V IGBTs using the MPT concept optimized for drives applications. In addition to channel width optimization, the cell design was adapted to the best trade-off between turn-on losses and voltage slope (dv/dt) at low currents. An improvement of $V_{CE,sat}$ by 600 mV at same E_{off} was achieved. Furthermore, at a fixed voltage slope of, e.g., 5 kV/µs a reduction of E_{on}/A by ~10% was reached. In addition to the above mentioned performance improvement, the MPT-IGBT is able to maintain the turn-off softness and short-circuit ruggedness of the previous generation. Thermo-camera imaging was used to demonstrate the enormous $V_{CE,sat}$ improvement of MPT-IGBTs.

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