

On the Investigation of the “Anode Side” SuperJunction IGBT Design Concept

Marina Antoniou, Neophytos Lophitis, Florin Udrea,
Friedhelm Bauer, Umamaheswara Reddy Vemulapati, Uwe Badstuebner

Abstract— In this paper we present the “Anode Side” SuperJunction Trench Field Stop+ IGBT concept with drift region SuperJunction pillars placed at the anode side of the structure rather than the cathode side. The extent of the pillars towards the cathode side is shown to pose a trade-off between fabrication technology capabilities (and cost) versus the device performance, by extensive TCAD simulations. The proposed device structure simplifies the fabrication requirements by steering clear from the need to align the cathode side features with the SuperJunction pillars. It also provides an extra degree of freedom by decoupling the cathode design from the SuperJunction structure. Additionally, the presence of SuperJunction technology in the drift region of the “Anode Side” SJ Trench FS+ IGBT results in 20% reduction of on-state losses for the same switching energy losses or, up to 30% switching losses reduction for the same on-state voltage drop, compared to a 1.2kV breakdown rated conventional FS+ Trench IGBT device. The proposed structure also finds applications in Reverse Conducting IGBTs, where a reduced snapback can be achieved, and in MOS-Controlled Thyristor Devices.

Index Terms—Insulated Gate Bipolar Transistor, Point Injection, SuperJunction (SJ), Field Stop

I. INTRODUCTION

THE presence of the SuperJunction (SJ) structure in the drift region of the conventional MOSFET [1] results in the realisation of devices with significantly reduced on-state losses. At the same time the modified electric field distribution allows for the device to be made thinner while maintaining the breakdown voltage. The demonstration of the optimised SJ IGBT structure at the theoretical [2-4] and more recently at the experimental level [5] proved the potential of these structures. Further, the combination of a highly efficient IGBT operation with suppressed snapback Reverse Conducting capability is a highly desirable objective [6].

The SJ IGBT exhibits a distinctively different behaviour to that of the SJ MOSFET [2]. In IGBTs, the current conduction

is bipolar, i.e. both electron and holes contribute to the conduction of current. The exact positioning of pillars in the drift region affects the charge distribution in the on-state and, determines the charge extraction rate under switching conditions. More specifically, there are two geometry variations which can considerably affect the device performance. The first one is that when the p-pillar is connected to the cathode p-base [4]. In this case, the bipolar conduction of current turns unipolar at the cathode side with electrons and holes following the n-pillar and p-pillar paths respectively. The increase of the pillars concentration contributes to the on-state resistance drop of the devices. At the same time, the presence of the n/p -pillars deep in the drift region serves to collect the charge directly from the proximity of the anode side of the device. The second geometry variation which also gives the best device performance, requires the p-pillar to be disconnected from the p-base but in close proximity to it [4]. The result of this is that the current conduction is bipolar throughout the device. In this case, the presence of the p/n -pillars does not improve the on-state resistance but primarily affects the device speed under switching conditions. The deeper and more highly doped the pillars, the more effective they are because the multiple junctions in the drift region help to extract the charge more effectively. It is therefore evident that the positioning of the pillars is very important. In this work a previously calibrated simulation setup [2], [4], is used to investigate the performance of a new IGBT design concept that features the SuperJunction technology at the anode side.

II. THE SUPERJUNCTION FABRICATION APPROACH

The Anode Side SJ IGBT is compared to the Trench FS+ in Figure 1. It consists of the trench-type MOS electron channel (cathode side) and the anode side, which features a p-anode and an n-buffer layer. The drift region employs the SJ pillars,

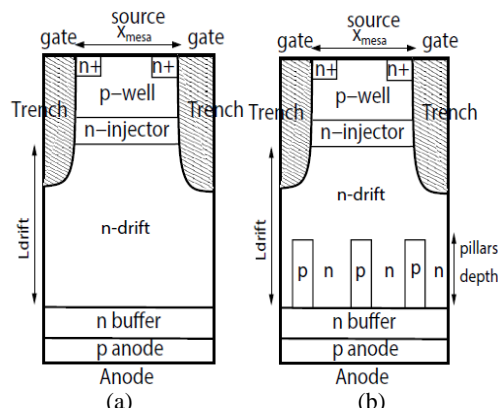


Figure 1: The Trench FS+ IGBT cell and the “Anode side” SJ IGBT structure (not to scale).

Manuscript received April 03, 2017.

M. Antoniou, and F. Udrea are with the Electrical Engineering Department, University of Cambridge, Cambridge CB3 0FA, U.K. UK (phone: +44 (0)1223 748 311; fax: +44 (0)1223 748 348; e-mail: ma308@cam.ac.uk). N. Lophitis is with the Faculty of Engineering Environment and Computing, Coventry University, Coventry CV1 5FB, U.K., and also with the Electrical Engineering Department, University of Cambridge, Cambridge CB3 0FA, U.K. Friedhelm Bauer, Umamaheswara Reddy Vemulapati, and Uwe Badstuebner are ABB Switzerland Ltd., Corporate Research, Segelhofstrasse 1K, 5405 Baden-Dättwil, Switzerland.

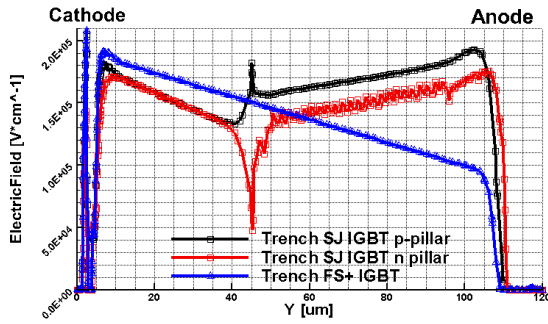


Figure 2: The electric field distribution of the Trench+ IGBT and the “Anode side” SJ IGBT with a 120μm thickness under blocking conditions.

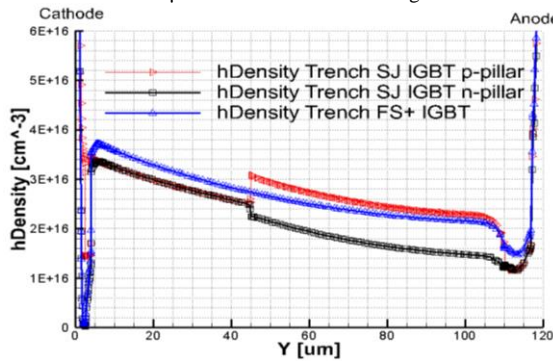


Figure 3 The hole density concentration of the Trench FS+ and the “Anode side” SJ IGBT across the drift region under on-state conditions (100A/cm²)

which are formed using a trench and refill techniques. Therefore, due to fabrication limitations, the extension of these pillars can be up to about 65μm deep under the state-of-art techniques. Very importantly the proposed device structure requires no cathode and SJ alignment. In the same manner the proposed design offers the complete decoupling of the cathode side pitch and the pillar wide design allowing better control of the saturation current and short circuit capability by independently controlling the cathode device design [7]. The proposed fabrication implies that the n- doped wafer is treated from the anode side with the p/n pillars, the n-buffer and the p-anode layer formed successively. The total thickness of a 1.2kV structure is 120μm. Fig.2 shows the electric field distribution of the Trench FS+ and the SJ IGBT (anode side pillars) under blocking conditions along both the n and p-pillar. In both cases, the presence of the n+ injector layer at the cathode side controls the critical electric field that appears at the p-well/ n-injector junction. The usual trade-off applies; a

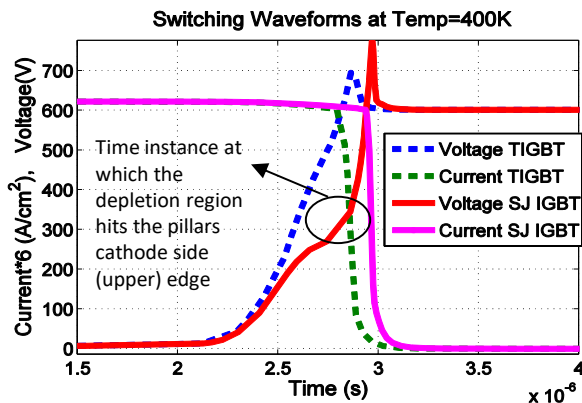


Figure 4: The switching waveform of the Trench FS+ and the “Anode side” SJ IGBT (65 μm thick pillars).

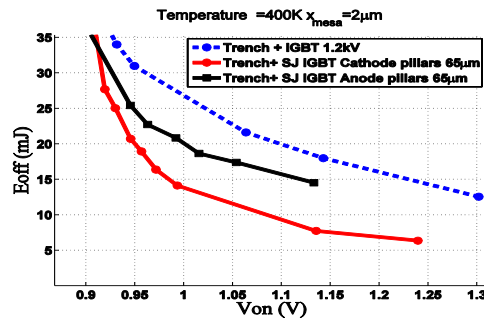


Figure 5: The technology curves of the Trench, the SJ IGBT with the cathode and anode side pillars (120μm device thickness)

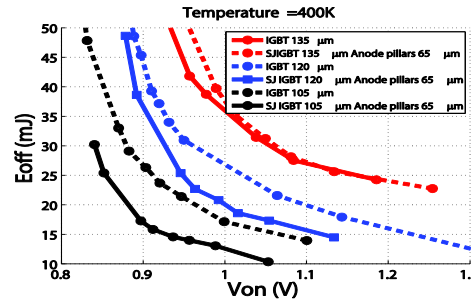


Figure 6: The technology curves of the Trench + IGBT and the “Anode side” SJ IGBT for 105, 120 and 135 μm total device length. The smaller the drift layer thickness, the closer the SJ pillars are to the cathode side.

higher doped n+ injector leads to lower breakdown voltage but improved on-state performance [8]. As shown, the presence of the SJ alters the shape of the field resulting to a higher voltage being supported for the same device thickness. As a result, the device can be made thinner, while maintaining the same breakdown voltage (e.g. same voltage class). It is also worth noticing the two distinctive electric peaks appearing in the middle and the anode side of the drift region. The presence of these peaks of electric field are due to the junctions between the n-drift with the SJ pillars and SJ pillars with the n-buffer respectively (the maximum electric field is maintained below the critical electric field at all times of the device operation).

III. ON-STATE AND SWITCHING PERFORMANCE

The presence of the SJ structure at the anode side of the device translates into higher electric field at the n buffer edge (as shown in Figure 2). The electric field has to be therefore dropped to zero within the buffer layer to avoid punch-through. As a result, the field stop condition of the IGBT imposed the increase of the n-buffer layer doping. This necessary modification of the n-buffer layer translates into change in the injecting efficiency of the p-anode layer (reduction of the holes injection into the drift region). Figure 3 shows the hole density concentration across the device for the Trench FS+ and the SJ IGBT (along the p and n SJ pillars); for the same p-anode doping the charge distribution is lower, hence the voltage drop across the device is expected to be higher (operating at 100A/cm²). Therefore, in order to match the on-state performance of the two structures the p-anode layer doping has to increase.

Figure 4 shows an example of the differences between the turn-off waveforms of a Trench FS+ and a SJ IGBT. During turn-off, the p-well/ n- drift junction remains the main voltage-

supporting junction. As the voltage increases, the depletion region expands towards the anode side. Once it reaches the p-pillar, the depletion region starts to expand laterally. The earlier the edge of the depletion region reaches the p-pillar, the earlier the lateral expansion begins. During this instance, the voltage rise rate decreases because of the presence of the SJ layers and the resulting doping difference. As soon as the SJ pillars become fully depleted, the voltage increases more abruptly. The intermediate slow voltage rise and the subsequent faster rate of voltage increase is what is expected when there exists a doping non-uniformity within the drift region. It is indeed a typical behavior in SuperJunction structures; the steep increase in dV/dt is a common switching characteristic of SuperJunction structures due to the abrupt reduction in the output capacitance once the SJ layers are depleted. This effect reduces the switching losses but has negative effects such as increased EMI and high peak anode voltage- it can be however easily controlled through the careful gate-drive design.

Figure 5 shows the technology curves of the Trench FS+ and the anode side and cathode side SJ IGBT structures of total device length $120\mu\text{m}$. In the same manner fig.6 shows the corresponding technology curves for three Trench FS+ and "anode side" SJ IGBTs with different total device thickness (both for the Trench FS+ and the SJ structure) while maintaining the same pillar depth; this figure highlights the limit of the thickness of the SJ structure for which the anode side SJ pillar offers better switching speed. As expected, the cathode side pillars (disconnected from the p-base but kept very close to the cathode side) give the best technology curve for the same length. The proposed anode side SJ pillars (with $65\mu\text{m}$ pillars depth) still offer a significant improvement to the performance of the conventional Trench FS+ IGBT. As already explained, the SJ in the drift region allows for the devices thinning as well as the improvement in switching speeds but the effect of it reduces as the "depth" measured from the anode side gets smaller. Based on the results presented in fig. 6, the "Anode side" SJ structures ($120\mu\text{m}$) against the conventional Trench FS+ IGBT ($135\mu\text{m}$), the SuperJunction device achieve in 20% reduction of on-state losses for the same switching energy losses or, up to 30% switching losses reduction for the same on-state voltage drop.

For a proposed solution the $65\mu\text{m}$ deep pillars are placed at the anode side of the structure, therefore the fabrication is not limited by the processes at the cathode side. Indeed some of the switching benefit is reduced compared to the cathode side pillars but we can still obtain significant improvement in the performance of this device. Further, in both cases (anode side and cathode side SJ structures) the deeper (longer) the pillars the better the performance. The longer/deeper the pillars, the closer they are to the cathode side. Consequently, the depletion region hits the pillars earlier during the turn-off, the delay occurs at a lower voltage and the corresponding energy losses are smaller. For that reason there is a trade-off between the SJ positioning (and therefore the length/depth and the ease to manufacture the SJ pillars) and the switching speed.

Furthermore the "anode side" SJ IGBT can contribute to another very important Reverse Conducting IGBT

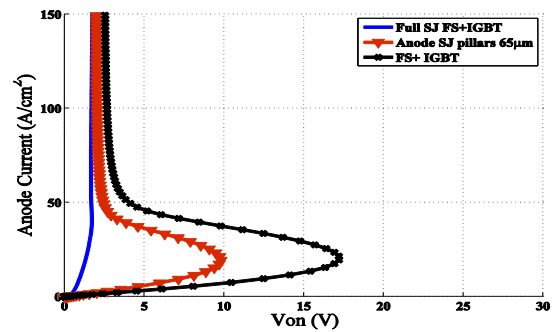


Figure 7: The snapback phenomenon; On-state characteristics for the IGBT, the full SJ and the anode side SJ pillars ($65\mu\text{m}$).

performance hindering issue; the snapback phenomenon. It was previously demonstrated that the presence of the SJ structure can suppress the voltage snapback observed in the on-state characteristic [6]. Here, as shown on Figure 7, the "anode side" SJ IGBT can cut the voltage snapback by up to 35% given the $65\mu\text{m}$ pillars extension. Of course the utilization of the full SJ drift region does completely suppress this phenomenon. Further applications of the anode side SJ concept could include in power devices could include the MOS-Controlled Thyristor where reduction in the switching losses is a very important aspect to the device operation.

IV. CONCLUSION

In this paper we present the energy efficient "Anode side" SJ IGBT. The pillars can be introduced in the drift region from the anode side which makes the fabrication process easier. We have also identified a trade-off between the SJ pillars distance from the main voltage-supporting junction (cathode side) and the device switching speed (and performance). Given the state of art fabrication techniques the proposed device is shown to be able to be fabricated relatively easy and can offer 30% improvement in performance compared to the conventional Trench FS+ IGBT.

V. ACKNOWLEDGMENT

Dr M. Antoniou wishes to thank EPSRC Centre for Power Electronics-UK for support.

REFERENCES

- [1] G. Deboy, N. Marz, J. P. Stengl, H. Strack, J. Tihanyi and H. Weber, "A new generation of high voltage MOSFETs breaks the limit line of silicon," International Electron Devices Meeting 1998. Technical Digest (Cat. No.98CH36217), San Francisco, CA, USA, 1998, pp. 683-685. doi: 10.1109/IEDM.1998.746448
- [2] M. Antoniou, F. Udrea and F. Bauer, "Optimisation of SuperJunction Bipolar Transistor for ultra-fast switching applications," *Proceedings of the 19th International Symposium on Power Semiconductor Devices and IC's*, 2007, pp. 101-104. doi:10.1109/ISPSD.2007.4294942
- [3] Bauer, F; "The super junction bipolar transistor: a new silicon power device concept for ultra-low loss switching applications at medium to high voltages", *Solid State Electronics*, vol. 48, pp. 705-714, 2004. <https://doi.org/10.1016/j.sse.2003.09.017>.
- [4] M. Antoniou, F. Udrea, F. Bauer and I. Nistor, "The Soft Punchthrough + Superjunction Insulated Gate Bipolar Transistor: A High Speed Structure With Enhanced Electron Injection," in *IEEE Transactions on Electron Devices*, vol. 58, no. 3, pp. 769-775, March 2011. doi: 10.1109/TED.2010.2101076

- [5] K. H. Oh, J. Kim, H. Seo, J. Jung, E. Kim, S. S. Kim and C. Yun., "Experimental investigation of 650V superjunction IGBTs," 2016 28th International Symposium on Power Semiconductor Devices and ICs (ISPSD) 2016, pp. 299-302. doi: 10.1109/ISPSD.2016.7520837
- [6] M. Antoniou, F. Udrea, F. Bauer and I. Nistor, "A new way to alleviate the RC IGBT snapback phenomenon: The SJ solution," 22nd International Symposium on Power Semiconductor Devices & IC's (ISPSD), June 2010, pp. 153-156.
- [7] A. Nakagawa, "Theoretical Investigation of Silicon Limit Characteristics of IGBT," 2006 IEEE International Symposium on Power Semiconductor Devices and IC's, Naples, 2006, pp. 1-4. doi: 10.1109/ISPSD.2006.1666057
- [8] M. Rahimo, A. Kopta and S. Linder, "Novel Enhanced-Planar IGBT Technology Rated up to 6.5kV for Lower Losses and Higher SOA Capability," 2006 IEEE International Symposium on Power Semiconductor Devices and IC's, Naples, 2006, pp. 1-4. doi: 10.1109/ISPSD.2006.1666064