The p-ring Trench Schottky IGBT:

A solution towards latch-up immunity and an enhanced safe-operating area

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Abstract— A novel Trench IGBT design, namely the p-ring Trench Schottky IGBT, with improved latch-up immunity and an enhanced safe-operating area is proposed. This design improves the performance of the FS+ IGBT by facilitating the collection of holes through a p-doped (p-ring) buried region connected through a Schottky contact to the source/cathode contact. This unique structure approach allows the improvement in the device reliability and it is shown under numerical studies to be highly effective in expanding the safe operating area (SOA), suppress dynamic avalanche, improving the latch up robustness and having the potential to improve the device switching operation.

Keywords— *Junction Barrier Schottky diodes, JBS, SiC, surge current, SiC diodes, MPS.*

I. INTRODUCTION

In recent years, power semiconductor devices have been attracting strong attention due to the quest for higher efficiency making them a major field of research. IGBTs are applied to vast range of power electronic applications, especially medium and high power equipment, such as ac drive motion control, UPS, renewables (wind and solar), and others; the IGBT has become one of the most utilized power semiconductor switches in the market due to the extensive development and improvement of the basic chip structure and packaging technologies.

Over the years, several effective solutions towards the enhancement of the electron injection at the cathode side of the IGBT structure have been proposed with examples including the IEGT (Injection Enhanced Gate Transistor) [1], the CSTBT (Carrier Store Trench Bipolar Transistor) [2], the Trench EST (Emitter Switched Thyristor) [3], the HiGT (High Conductivity IGBT) [4] and the Fin P-body IGBT [4]. More recently the authors have proposed the p-ring IGBT [5,6], where the bottom of the trench structures are covered by a p-doped layer in order to improve the on-state performance and reliability without affecting the device rating (fig.1). The presence of a p-ring was shown to significantly reduce the electric field strength at the critical oxide trench gate region without affecting the device breakdown voltage. Furthermore, due to local charge compensation the p-ring IGBT can also reduce the on-state losses while maintaining low switching losses.

II. DEVICE STRUCTURE

The proposed device is depicted in Fig.2. The anode side of the “p-ring Trench Schottky IGBT” structure is identical to the p-ring FS+ IGBT (Fig.1) [5, 6]; it consists a p anode layer and an n buffer layer. The cathode side employs a trench gated structure, an n-doped enhancement layer and p-doped buried layers (p-rings), which extend in the third dimension either continuous of in a form of periodic islands. As previously shown by the authors, the “p ring” layer attached to the gate oxide acts in two very beneficial roles for the device operation roles (a) it compensates for the intentional doping increase of the n-enhancement (n-enh) layer through a local 3D RESURF effect; in turn the presence of a highly doped n layer (within the

Figure 1: Schematic of a p-ring Trench IGBT structure

Figure 2: Schematic of a p-ring Trench Schottky IGBT structure

Figure 3: The p-ring Trench Schottky IGBT details on the cathode side

Figure 4: Breakdown Characteristic of the p-ring Trench Schottky IGBT

MESA region) results in significant on-state losses reduction without compromising the switching performance or the breakdown rating of the device. (b) The p-ring IGBT is also allowing for the lowering of high electric field peaks at round the trench bottom. As a result the electric field distribution around the oxide corners are significantly lower, hence issues low hot carrier injection and loss in device reliability are less prominent.

In the new proposed structure a Schottky contact is placed at the trench bottom through an oxide opening (Fig.3) at the surface of the contact-connected p-ring. The p-ring layer has a retrograde profile so that the doping concentration at the surface (where the Schottky contact is placed) is lower than deeper in the device. The actual barrier shape (height and width) of the Schottky contact can therefore be adjusted by controlling the doping concentration at the interface with the Schottky contact and by the appropriate selection of the metal layer or stack of metal layers.

III. DEVICE OPERATION

The presence of a trench bottom contact which consists of an opening in the gate oxide and the replacement of it with a grounded contact allows for hole current conduction through the p anode/n-drift/p-ring path – something that does not occur in a conventional trench gated IGBT as the gate oxide covers the entire trench internal surface. In the conventional case the hole current is collected at the cathode surface p-base/body contact. In the case of a purely ohmic p-ring contact in the trench bottom opening the amount of holes collected through this trench bottom opening is, as expected, would be exceedingly high, degrading the plasma modulation at the cathode side- critical for a favourable on-state performance. On the contrary, the presence of a Schottky contact, which consists of a grounded Schottky contact, permits for a limited the amount of holes to collected in the on-state. Hence the plasma concentration at the top side of the device can be modified by adjusting hole current collecting through this trench bottom contact. The effect of the “p-ring Schottky contact” was analyzed through 3D-simulations. Figure 4 shows the simulated breakdown characteristic of the Schottky IGBT. The specific

Figure 5: HDensity across the A-A' vertical outline for p-ring IGBT, Trench Schottky and Trench Ohmic contact IGBT structure.

Figure 6: On-state output characteristic of the p-ring IGBT, Trench Schottky and Trench Ohmic IGBTs at 400K.

Figure 7: On-state characteristic of the p-ring Trench IGBT (electron and holes current component).

Figure 8: (a) On-state characteristic of the Trench Ohmic contact IGBT (electron and holes current component) (b) On-state characteristic of the Trench Schottky contact IGBT (electron and holes current component)

design is shows a device breakdown in excess of 1.2kV. Figure 5 shows the plasma concentration for the p-ring IGBT, the Ohmic contact and Schottky contact IGBTs ($V_g=15V$, $I_{CE}=100A/cm^2$) along the dashed line AA' as indicated on fig.3. From this figure it is clear that the presence of this contact affects the on-state performance (on-state voltage drop), the extent of which, is controlled through the nature of the contact (Ohmic/Schottky).

Figure 6 shows the on-state characteristics of the conventional (p-ring) Trench, p-ring Schottky and p-ring Ohmic IGBTs. An on-state improvement of 25% (at $I_D=100A/cm^2$) can be observed by the Schottky contact over the Ohmic counterpart. However, as expected, the on-state performance on the Schottky IGBT is degraded compared to the conventional structure by about 5%. Focusing on the exact current component ratios, figure 7 shows the corresponding electron and hole current components of the emitter (source) current in a ratio of two to one parts. Figure 8(a,b) show the corresponding figures for the Ohmic and Schottky p-ring IGBTs; as expected, part of the hole current is taken by the trench Ohmic and Schottky contacts respectively and the

stronger the collection of holes, the greater the reduction in plasma concentration at the cathode side. Therefore the flow of holes through the Ohmic contact is much stronger compared to its Schottky counterpart by a factor of two (green curves). As already mentioned above, the control of the amount of hole current through the trench contact allows for higher plasma concentration at the cathode side which in turn translates in to lower on-state losses. The extent of holes collection can in reality be controlled by the workfunction of the metal layer or stack of metal layers of the Schottky contact or the surface doping concentration of the p-ring. In addition the designer of such structure can utilise the 3-dimensional area of such contacts as a means of adjusting/ limiting the desired amount of hole current collected at the bottom of the trenches where the opening and contact is present.

Figure 9(a) shows the current turn-off characteristic of a conventional IGBT; the red line shows the total emitter/source and the blue line shows the hole current component that reached the source side. Figure 9(b) shows the corresponding turn off waveforms of a trench Schottky IGBT with the components of current carried by the Schottky contact (green

Figure 9: (a) Current turn-off characteristic of the Trench IGBT (electron and holes current component), (b) Current turn off output of the Trench Schottky IGBT (electron and holes current component).

Figure 10: Dynamic Avalanche – (top row) p-ring Trench IGBT and Schottky IGBT turn-off – second row shows the first derivative of Voltage [8] respectively.

Fig. 11: Unclamped Inductive switching of the conventional p-ring Trench IGBT device fails before $pw=35\mu s$.

Figure 12: Unclamped Inductive switching of the p-ring Trench Schottky IGBT device- survives up to $pw=39\mu s$.

curve) and current, the black line shows the electron current component surface emitter contact (blue); the Schottky contact actively collects the major part of hole current deeper from the device lowering the risk of the parasitic pnp latch-up, either during turn-off, dynamic avalanche or short-circuit conditions.

In order to further examine the benefits offered by the proposed device structure we have been investigating the dynamic and short circuit conditions response against the conventional design. Figure 10 shows the turn-off voltage and current waveforms of the conventional IGBT. The second figure shows the first derivative of anode voltage (dV_{ce}/dt). Under dynamic avalanche-free conditions this parameter should be increasing linearly until the voltage reaches its maximum voltage (up until the point where the turn off process is dominated by the sweeping out of the plasma and by building up the depletion region [7, 8]). For the p-ring IGBT this is not continuously increasing; on the contrary the voltage experiences a reduction in increase and a slump in its derivative. This is a typical result of dynamic avalanche occurring during turn-off; in this case additional charge is supplied by the dynamic avalanche and it also slows down the current fall when compares to the dynamic avalanche free case. In the Schottky IGBT case (as shown in figure 7), in contrast to the conventional IGBT structure, the absence of Dynamic avalanche is evident with the dV_{ce}/dt component increasing continuously up until voltage reaches its maximum value. Hence, the Schottky contact presence allows for a deeper collection of holes from the device drift avoiding the triggering of any parasitic component and the onset of dynamic avalanche.

Furthermore, figures 11&12 show the unclamped inductive switching (UIS) of the p-ring Trench IGBT device and the Schottky IGBT device respectively. This test involves the application of a gate pulse width (PW) and the examination of the device turn-off capability. In the conventional IGBT case the device fails to turn off for pulse width longer than $35\mu s$ (Fig. 11) whereas the trench Schottky IGBT survives up to $39\mu s$ (Fig.12). From these figures we can also see the reduction in the self-heating effect with the failing conventional IGBT reaching above 750K. As previously mentioned the behaviour (i.e. amount of holes collected through the trench Schottky contact) and avalanche resilience of the proposed design can be adjusted both through the design and Schottky contact properties.

IV. CONCLUSIONS

The “Trench Schottky IGBT” is a very promising structure has the potential to overcome the limitations in the current state of the art design both in terms of normal operation performance and reliability. The Schottky contact allows both the adjustment the plasma concentration at the cathode side of the device and it allows the enhanced collection of holes during off-state or short-circuit. Therefore, the p-ring acts to (i) help the collection of holes through the Schottky contact (and improve the switching losses), (ii) improve the dynamic avalanche induced mode failures (iii) protect the trench bottom corners against the high electric fields in the off-state, in a similar fashion to the conventional p-ring and (iv) compensate the adjacent enhancement layer. It should also be noted that, the collection of holes occurs through a combination of Schottky and ohmic contacts (source contacts). Both the Schottky and the ohmic contacts are connected to the source and the ratio of their areas is important for a good trade-off between on-state voltage drop and SOA. Hence, an optimised 3D Schottky-contact design can facilitate an optimum trade-off between device operation and reliability.

REFERENCES

- [1] M. Kitagawa et al., "A 4500 V injection enhanced insulated gate bipolar transistor (IEGT) operating in a mode similar to a thyristor", IEDM Tech. Dig., pp. 679-682, Dec. 1993.
- [2] H. Takahashi et al. Carrier Stored Trench-Gate Bipolar Transistors (CSTBT), ISPSD 1996.
- [3] M. Mori et al. A Novel High-Conductivity IGBT (HiGT) with Short Circuit Capability, ISPSD 1998.
- [4] Y. Miyaoku et al., "Compact modeling and analysis of the Partially-Narrow-Mesa IGBT featuring low on-resistance and low switching loss," IEEE ISPSD, 2015.
- [5] H. Feng, W. Yang, Y. Onozawa, T. Yoshimura, A. Tamenori and J. K. O. Sin, "A 1200 V-class Fin P-body IGBT with ultra-narrow-mesas for low conduction loss," ISPSD, 2016.
- [6] M. Antoniou et al., "Experimental demonstration of the p-ring FS+ Trench IGBT concept: A new design for minimizing the conduction losses," IEEE ISPSD, 2015.
- [7] M. Antoniou et al., "Novel Approach Toward Plasma Enhancement in Trench-Insulated Gate Bipolar Transistors," in IEEE Electron Device Letters, vol. 36, no. 8, pp. 823-825, Aug. 2015.
- [8] Geissmann, S., et al. "Extraction of dynamic avalanche during IGBT turn off," Microelectronics Reliability 76 ,2017.
- [9] A. Bryant, et al. Investigation into IGBT dv/dt during turn-off and its temperature dependence in, IEEE Trans. Power Electron. 26 (10) (2011) 3019–3031.