Extended Abstracts of the 1994 International Conference on Solid State Devices and Materials, Yokohama, 1994, pp. 760-762

Injection Efficiency Enhancement in Dynamic Trench Gate Emitter (DTGE) for 4500 V MOS Gate Transistor (IEGT)

Mitsuhiko Kitagawa, Akio Nakagawa and Ichiro Omura

Research and Development Center, Toshiba Corporation
1,Komukai Toshiba-cho,Saiwai-ku,Kawasaki 210,Japan
Phone: 044-549-2138, Fax.: 044-549-2259

The injection enhancement effect of trench gate structure is investigated. The blocking voltage range in which a novel trenched gate emitter structure effectively reduces forward voltage drop is shown for the first time, by developing an analytical 1-dimensional model. It is shown that the emitter structure is not only more effective for high voltage devices such as the 4500 V devices, but also the emitter structure effectively decreases the forward voltage drop of several hundred blocking voltage devices, especially above 500 V, without degradation of turn-off capability.

1. Introduction

The 4500 V Injection Enhanced Gate Transistor (IEGT) has been proposed as a promising future high-voltage power device, capable of replacing and improving GTO-thyristors [1]. Conventional IGBTs have been widely accepted in various high-power application fields because they offer easy MOS gate controllability and a wide safe-operating area [2]. However, IGBTs suffer a large voltage drop if they are designed to exceed 2000 V [3]. This is because electron injection from the MOS gate is insufficient, compared to that of thyristors. It was found that a novel trench MOS gate structure acts as an emitter with a high electron injection efficiency and realizes the thyristor-like low forward voltage drop in the proposed 4500 V IEGT [1]. However, the precise physical behavior of the trench emitter and the blocking voltage range in which the forward voltage is fully reduced have not been reported as yet.

2. Precise 1-D Model for DTGE

A complete 1-dimensional analytical model has been developed to quantitatively discuss the forward voltage drop of IEGTs. In the structure of the IEGT, the management of electron and hole current is carried out in the area shown by a dotted line in Fig. 1, the structure is called a Dynamic Trench Gate Emitter (DTGE), which means the created emitter layer dynamically acts as an emitter.

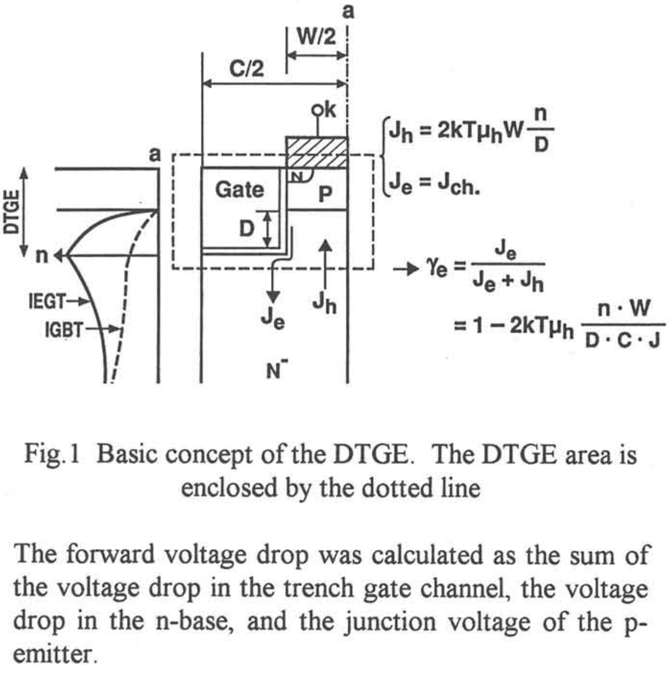

Fig. 1 Basic concept of the DTGE. The DTGE area is enclosed by the dotted line

The forward voltage drop was calculated as the sum of the voltage drop in the trench gate channel, the voltage drop in the n-base, and the junction voltage of the p-emitter.

$$V_F = V_{ch} + V_{n\text{-base}} + V_{bi}$$

(1) Vch

The voltage drop consists of the channel voltage drop and the diffusion voltage due to carrier storage.

$$\begin{aligned} V_{ch} &= V_{MOS.} + V_{diff.} \\ &= R_{ch} \cdot J_e + (kT/q) \log (n_K/n_i) \end{aligned}$$

(2) Vn-base

The voltage drop in the n-base is analytically given by analytically solving the continuity equation :

$$dn^2/dx = n/La^2$$

where La denotes ambipolar diffusion length, with boundary conditions of the electron injection efficiency $\Gamma_{e,K}$ of the trench gate and the p-emitter hole injection efficiency $\Gamma_{h,A}$,

$$J_h = 2kT\,\mu_h W(n_k/D)$$
$$J_e = J - J_h$$
$$\Gamma_{e,K} = 1 - 2kT\,\mu_h W n_k/(DCJ)\text{ , for cathode side}$$
$$\Gamma_{h,A} = 1 - \alpha_a n_A{}^2/J\text{ , for anode side}$$

The injection efficiency of the trench gate is derived as shown in Fig. 1, assuming all the hole current flows by diffusion in the narrow n-region surrounded by the trench gates. $\Gamma_{h,A}$ is assumed to be a function of the carrier density at the anode side of the n-base.

(3) Vbi

The voltage drop in the junction of the p-emitter.

$$V_{bi} = (kT/q)\log(n_A/n_i)$$

3. Injection Enhancement with DTGE

Table 1 shows a comparison of electron injection between a DTGE, a junction n+ emitter and an IGBT. It is well known that the n+ emitter of a thyristor has a high injection efficiency of around 0.84~1.0.

	DTGE	Junction n^+ emitter	IGBT
Injection efficiency	$1\text{-}2kT \cdot \mu_h \cdot n \cdot (W/DC)/J$ $0.74 \sim 0.97$	~ 1	< 0.74
Origin of injection efficiency	Voltage drop at the channel	V_{bi}	

Table 1 Comparison of DTGE, conventional junction n+ emitter and IGBT

In contrast with to the n+ emitter of a thyristor, the injection efficiency of IGBTs is lower than 0.74 because the maximum value of the injection efficiency of IGBTs is limited to below the mobility ratio of electrons and holes [2,4].

The DTGE is a new concept for managing the flow of holes and the electrons by using an trench gate geometry. It has the ability to attain an injection efficiency of 0.74~0.97 through the choice of appropriate value for structural parameters C, D and W.

4. Effective Blocking Voltage Range

An effective blocking voltage range has been estimated by using the 1-D analytical model. Figure 2 shows a tradeoff curves between the on-state resistance and the n-base width. The carrier life-time at the n-base area is 0.1 μ s. Curve A shows the case of a low injection efficiency for electrons at around 0.74. Curve B shows the case of a high injection efficiency at around 0.94. The two curves cross at an n-base width of 20 μ m. Figure 3 shows the difference of the on-state voltage drop between curves A and B. The difference of on-state voltage drop becomes large with increasing n-base width. The crossing point depends on the life-time and the injection efficiency of anode p+ emitter. Taking practical switching devices into consideration, the crossing point is predicted, using the 1-D simulation to be between 20 to 100 μ m.

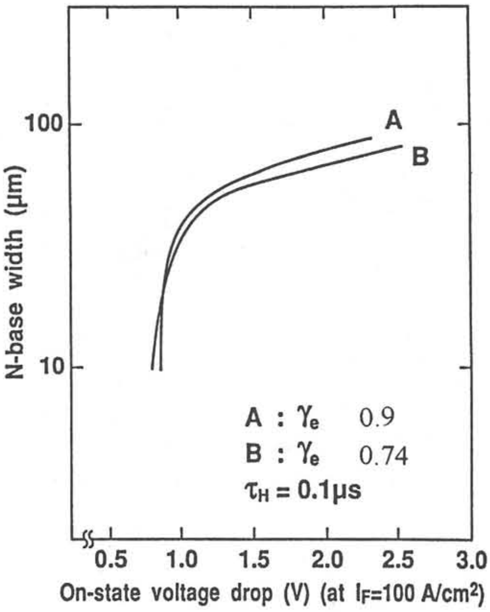

Fig. 2 Relationship between on-state voltage drop and n-base width for two different injection efficiencies

This means, that for a device with low injection efficiency, there is an area for reducing the on-state voltage drop with a thin n-base width less than 20 μ m. However, for a device which has an n-base width greater than 20 μ m, a high injection efficiency gives low on-state resistance. Figure 3 shows the improvement of the on-state voltage as a function of blocking voltage of IEGTs. It has been found that the improvement of the on-state voltage drop becomes large with increasing blocking voltage of IEGTs.

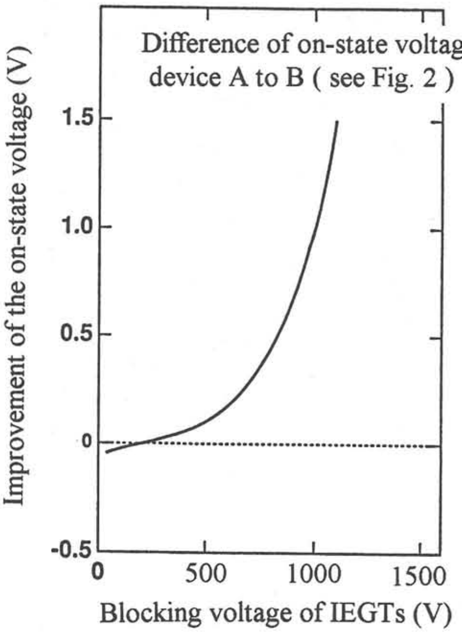

Fig. 3 Improvement of the on-state voltage with blocking voltage of IEGTs

5. Experimental Results

Figure 4 shows current-voltage characteristics for IEGTs with different injection efficiency. Curve A shows the case of high injection efficiency and curve B shows the case of low injection efficiency. As mentioned above, with increasing n-base width, the difference of the on-state voltage drop between devices with a low injection efficiency, such as IGBTs, and those with a high injection efficiency, such as IEGTs, becomes large. In the blocking voltage region of 4500 V, the on-state voltage drop of the conventional IGBT become too large.

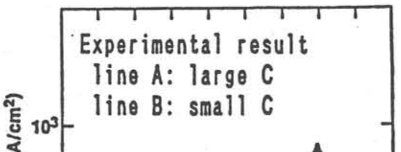

Fig.4 Current densities of IEGTs with on-state voltage, comparison of different C structural parameters

Figure 5 shows the experimental results which demonstrate that IEGTs with optimized DTGE have a low on-state voltage and a maximum latch up current density exceeding 1000 A/cm^2.

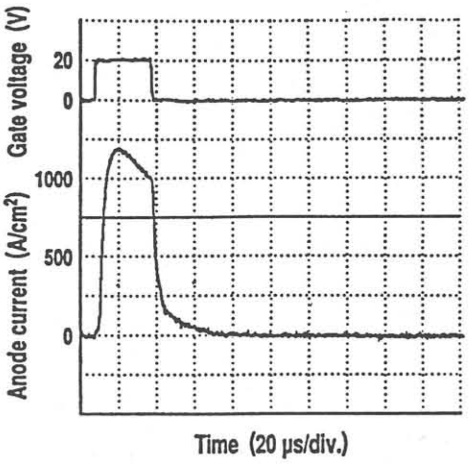

Fig. 5 Turn-off wave form of the 4500 V IEGT with DTGE (Experimental result)

6. Conclusions

The blocking voltage range in which the Dynamic Trench Gate Emitter (DTGE) effectively reduces forward voltage drop is shown by development of an analytical 1-dimensional model. The DTGE effectively decreases the forward voltage drop of several hundreds of blocking voltage devices, especially above 500 V, without degradation of turn-off capability.

We believe that the DTGE structure would make an essential contribution for improving high-voltage power devices in the high blocking voltage range from 2000 to over 4500 V.

Acknowledgments

The authors would like to thank Dr. Hiromichi Ohashi, Dr. Masaru Nakamura and Mr. Makoto Azuma for their encouragement throughout this work.

References

[1] M. Kitagawa, I. Omura, S. Hasegawa, T. Inoue and A. Nakagawa, IEDM Tec. Digest(1993), pp.679-682.
[2] A. Nakagawa, Y. Yamaguchi, K. Watanabe, H. Ohashi, IEDM Tec. Digest(1985), pp.150-153.
[3] K. Murakami, Y. Iwano, K. Mase, T. Ito, M. Kuwahara and T. Tsunoda, Power Conversion, proceedings,pp228-239, 1993.
[4] H. R. Chang and B. J. Baliga, IEEE Trans. Electron Device, Vol. 36, No.9, pp.1824-1829, 1989.