Jpn. J. Appl. Phys. Vol. 36 (1997) pp. 1411–1414
Part 1, No. 3B, March 1997

Study of 4.5 kV MOS-Power Device with Injection-Enhanced Trench Gate Structure

Mitsuhiko KITAGAWA and Akio NAKAGAWA
Toshiba Corporation, 1, Komukai Toshiba-cho, Saiwai-ku, Kawasaki 210, Japan

(Received September 13, 1996; accepted for publication November 19, 1996)

We propose two new MOS-power device structures, which realize lower on-state voltage than previously proposed injection-enhanced gate transistors (IEGTs). One is an improved IEGT (or IEGN), and the other is a MOS-controlled diode (or IEGD). Using 2-D numerical simulations, it has been confirmed that the IEGN and the IEGD realize a lower on-state voltage drop than the conventional IEGT, retaining MOS gate drivability. This means that the injection-enhanced gate structure improves the effective electron injection efficiency not only for transistor structures, but also for devices with a low-injection efficiency emitter. It has also been confirmed that the 4.5 kV IEGN and IEGD can operate under the same circuit conditions as a 4.5 kV GTO-thyristor.

KEYWORDS: power device, injection enhancement, MOS, trench gate, IEGT, IGBT, thyristor, carrier accumulation

1. Introduction

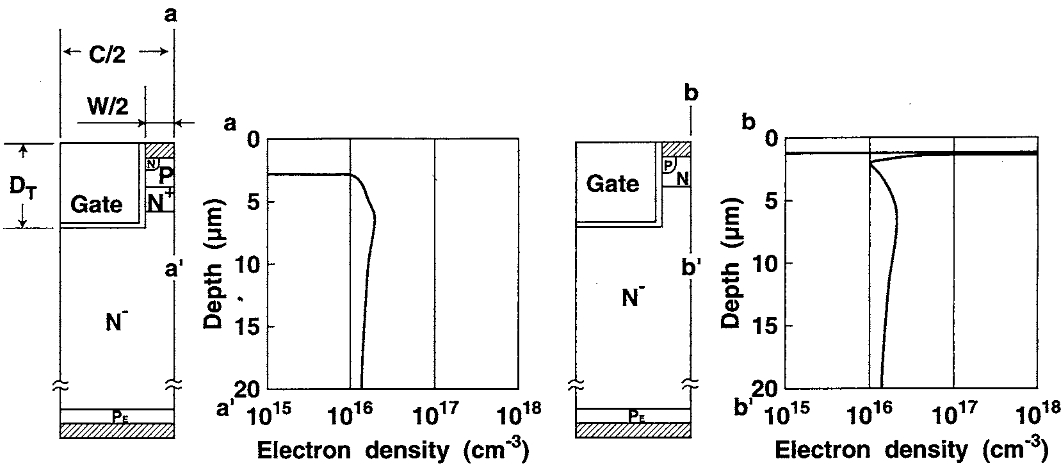
In 1993, injection-enhanced gate transistors (IEGTs) were proposed as promising high-voltage power devices.[1–3] In these devices, the new concept is to increase electron injection efficiency by reducing the amount of direct hole current flow into the cathode electrode by the novel trench gate structure. IEGTs achieve a thyristor-like carrier distribution and, as a result, realize a low on-state voltage, even for 4.5 kV devices. Since this device was proposed, many studies to improve the effective electron injection efficiency at the cathode side of the n-base layer have been reported.[4–6]

The trench gate structure is a key concept for power devices.[7] In this paper, we propose two new trench gate MOS-power device structures.[8] One is an improved IEGT (or IEGN, see Fig. 1(a)) in which we shows that a further improvement is obtained by introducing a barrier layer in the trench channel for hole current flow. The other is a MOS-controlled diode (or IEGD, see Fig. 1(b)) where the trench gate concept again plays an essential role in improving the current turn-off capability as well as the low on-state voltage.

2. IEGN

The improved IEGT (IEGN: injection-enhanced gate transistor with an n-type barrier layer) is characterized by an n-diffusion layer beneath the p-base, which works as an electrical barrier for direct hole current flow into the source electrode and further enhances the electron injection efficiency.

The cross-sectional view of an IEGN with electron carrier density distribution during the on-state in the middle of two trench gates is shown in Fig. 1(a). Figure 2 shows the calculated current-voltage curves of a 4.5 kV IEGN with the impurity concentration of the n-diffusion layer inside the trench channel beneath the p-base as a parameter. In this figure, lines A, B and C are the peak impurity concentrations of 5×10^{14}, 5×10^{15} and $5 \times 10^{16}\,\mathrm{cm}^{-3}$ respectively. The width of the n-diffusion layer is $1\,\mu$m, the lifetime of the n-base region is $4\,\mu$s and, the depth of the trenched gate is $4\,\mu$m. It is clearly seen that the n-diffusion layer of $5 \times 10^{16}\,\mathrm{cm}^{-3}$ improves the on-state voltage. The impurity concentration of the n-diffusion layer is smaller than that of a conventional n-emitter layer. The current-voltage curve of the IEGN with an n-diffusion layer of $5 \times 10^{14}\,\mathrm{cm}^{-3}$ is almost the same as that of the IEGT.



a : IEGN

b : IEGD

Fig. 1. Cross sectional view of IEGN and IEGD with electron carrier density in the middle of two trench gates.

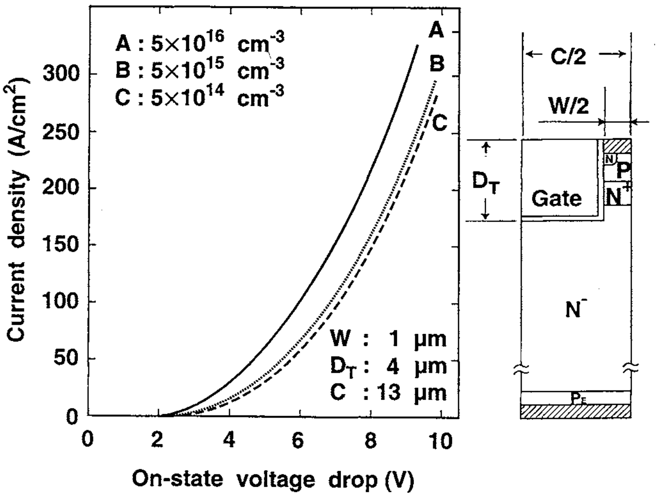


Fig. 2. Current-voltage curves for IEGN as a parameter of peak impurity concentration in the n-diffusion layer.

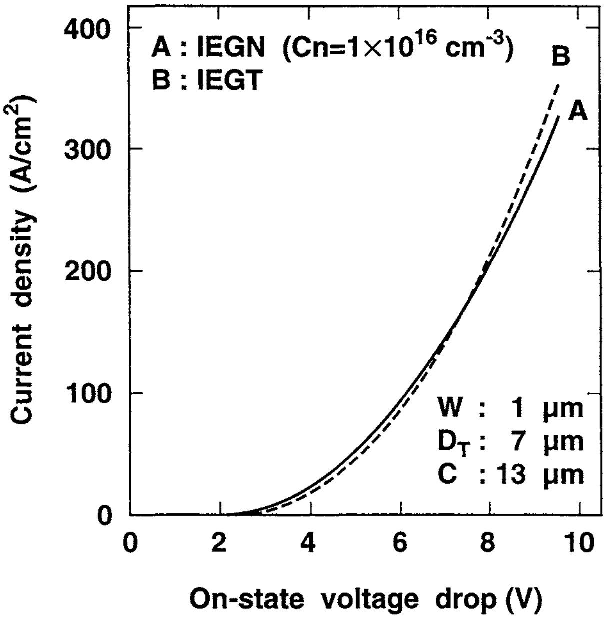


Fig. 3. Current-voltage curves for IEGN and IEGT.

However, the effects of the n-diffusion layer decrease as the trench gate depth increases. Almost no manifest improvement in the on-state voltage for deeper trench gate IEGNs is obtained, as seen in Fig. 3, where the current-voltage curves of an IEGT and IEGN with 7-μm-deep trench gates are compared.

It is numerically shown that the proposed 4.5 kV IEGN was successfully turned off even under a large inductive load. Figure 4 shows the simulated turn-off waveforms of the IEGN and the applied external circuit.

3. IEGD

A MOS-controlled diode (or IEGD: injection-enhanced gate diode) is based on the p-i-n diode structure, and is characterized by an n-emitter layer with a p-drain layer and a narrow current channel surrounded by two trench gates.

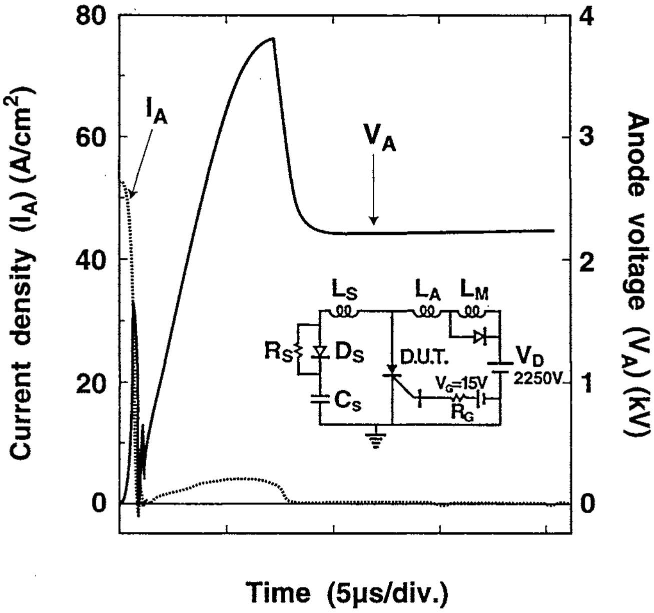


Fig. 4. Calculated turn-off waveform for IEGN.

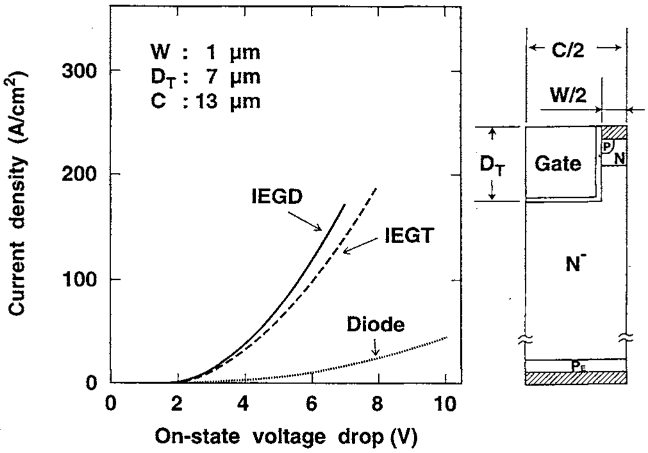


Fig. 5. Current-voltage curves for IEGD and diode with the same drain/emitter structure.

The cross-sectional view of the IEGD with electron carrier density distribution during the on-state in the middle of two trench gates is shown in Fig. 1(b). A p-drain layer is formed in the n-emitter. The essential point is that the trench channel width *W* is designed to be sufficiently small so that if the gate electrode is positively biased, the whole trench channel becomes an accumulated area layer. The accumulated n-layer works as an n-emitter layer and the device reduces to a p-i-n diode. On the other hand, if the gate electrode is negatively biased, the whole trench channel is inverted and forms an inverted p-layer. The IEGD is effectively reduced to a p-n-p transistor and achieves device turn-off.

The simulated 4.5 kV IEGD with a 7-μm-deep and 13-μm-wide trench gate attains an on-state voltage drop of 4.5 V at a 100 A/cm^2 current density with a lifetime of 4 μs for the 600 μm thick n-base. This small on-state voltage drop is superior to that of the conventional IEGT with the same n-base width. Figure 5 compares

Table I. Structural parameters of simulated models.

	D_T (μm)	W (μm)	C (μm)	Cn (cm^{-3})
IEGN	4	1	13	5×10^{14}, 5×10^{15}, 5×10^{16}
	7	1	13	1×10^{16}
IEGD	7	1	13	—

the current-voltage curves of the IEGD and a reference diode with the same fine drain/emitter pattern as the IEGD. Figure 6 shows a cross-sectional view of the reference diode with the same drain/emitter structure as the IEGD. The device parameters of the cathode structure are shown in Table I.

The simulated 4.5 kV IEGD was successfully turned off under a large inductive load. The turn-off mechanism of the IEGD was already proposed as that of IGPT.[9] Figure 7 shows the potential curve in the center of the trenched gates during the turn-off period. Figure 8 shows the hole density concentration in the center of the trenched gates during the turn-off period. It was confirmed that the electron current stops when the region, surrounded by the trenched gates, is negatively biased.

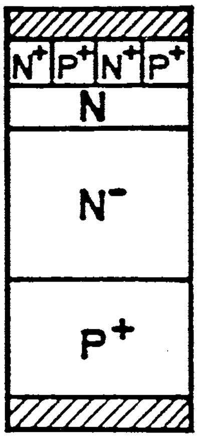


Fig. 6. Cross sectional view of the reference diode with the same drain/emitter structure as the IEGD.

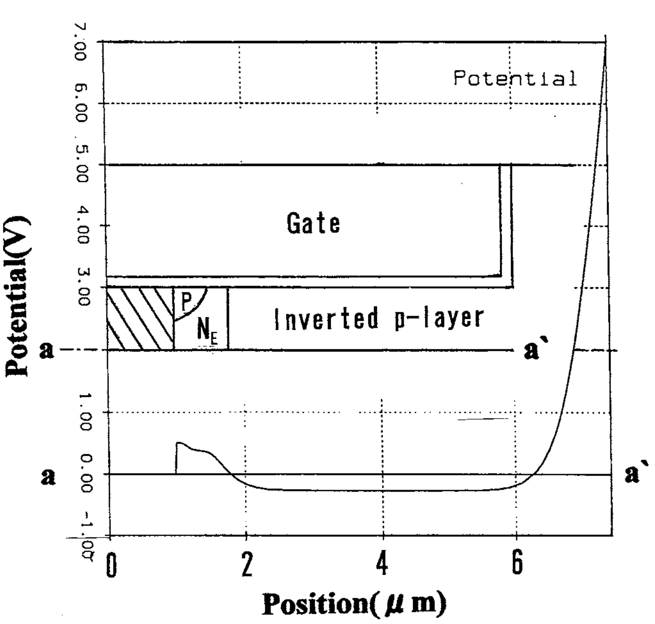


Fig. 7. Potential curve in the center of trenched gates in the turn-off period.

4. Discussion

In the IEGN structure, the n-diffusion layer acts as a barrier of the hole current, which then improves the on-state voltage. However, when the device is turned off, this n-diffusion layer prevents the hole current flow from the n-base to the cathode electrode. If the impurity concentration of the n-diffusion layer becomes larger than $5\times10^{16}\,\mathrm{cm}^{-3}$, the device suffers a low turn-off capability. In the case of the n-diffusion layer of $1\times10^{16}\,\mathrm{cm}^{-3}$, the improvement of the on-state voltage decreases as the trench gate depth increases. Almost no manifest improvement in the on-state voltage for deeper trench gate IEGNs has been obtained, as seen in Fig. 3, where the current-voltage curves of an IEGT and IEGN with 7-μm-deep trench gates are compared. As the trench depth increases, the effective injection efficiency of the IEGT increases, and the excess carrier density in the trench channel exceeds $1\times10^{16}\,\mathrm{cm}^{-3}$.[3] Then, the n-diffusion layer can not act as a barrier for holes.

In the IEGD structure, the injection-enhanced gate structure plays an essential role. The IEGD has no p-type base layer to stop the injection of electrons from the n-emitter. The distance between the trench gates must be less than 1 μm for the device to be turned off, also, the p-type drain layer and the n-type emitter layer must be formed inside the trench channel for the device to be turned off. In such device structures, it is inevitable that the electron injection efficiency of the n-emitter becomes low (see the current-voltage curve of the reference diode shown in Fig. 5). Then, an injection-enhanced

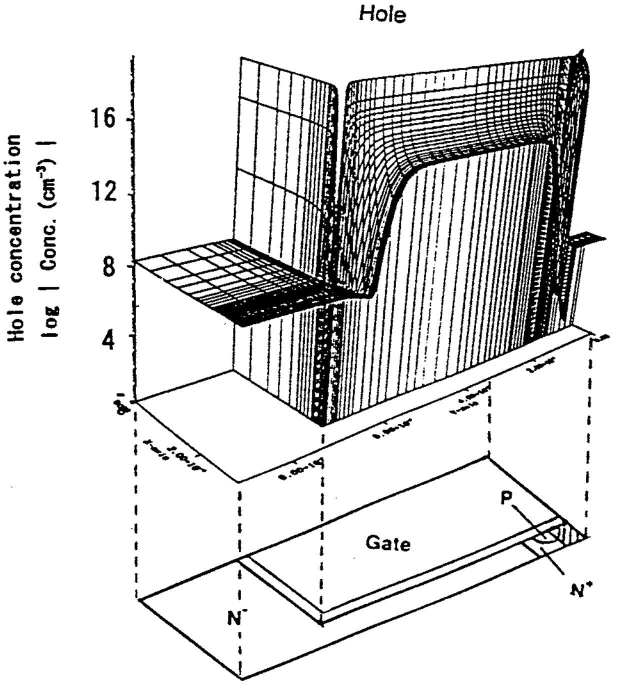


Fig. 8. Hole storage between the trench gates during blocking state and cross-sectional view of IEGD at cathode side.

gate structure is needed to attain a low on-state voltage drop and high turn-off capability. As is shown in Fig. 5, the injection-enhanced gate effect is effective not only as a transistor structure, but also as a diode with a low-electron injection efficiency. For the same reason, an injection-enhanced gate MCT (MOS-controlled thyristor), i.e. an IEGD with a thin p-type base layer inside the trench channel beneath the low-injection efficiency emitter, has a low on-state voltage drop and high turn-off capability compared to conventional trench gate MCTs.[8, 10]

5. Conclusions

By using 2-D numerical simulations, it has been confirmed that the IEGN and IEGD realize a lower on-state voltage drop than the conventional IEGT, retaining MOS gate drivability. The injection-enhanced gate structure improves the effective electron-injection efficiency not only for transistor structures, but also for conventional devices with a low-injection efficiency emitter. It was verified that the IEGD has a large turn-off ability because of the existence of hole storage between the two trench gates at the blocking state. It was also confirmed that the 4.5 kV IEGN and IEGD can operate under the same circuit conditions as a 4.5 kV GTO-thyristor.

Acknowledgements

The authors are grateful to Mr. Minami Takeuchi, Mr. Tsuneo Ogura, Dr. Hiromichi Ohashi, Mr. Yoshinari Uetake and Mr. Hideo Matsuda for their continuous interest in this work.

1) M. Kitagawa, I. Omura, S. Hasegawa, T. Inoue and A. Nakagawa: Tech. Dig. IEDM (1993) 679.
2) M. Kitagawa, A. Nakagawa and I. Omura: *Ext. Abstr.* 1994 Int. *Conf. Solid State Devices and Materials, Yokohama* (Business Center for Academic Societies Japan, Tokyo, 1994) p. 760.
3) M. Kitagawa, A. Nakagawa, K. Matsushita, S. Hasegawa, T. Inoue, A. Yahata and H. Takenaka: Proc. Int. Symp. Power Semiconductor Devices & ICs (1995) p. 486.
4) F. Udrea and G. A. J. Amaratunga: Proc. Int. Symp. Power Semiconductor Devices & ICs (1995) p. 190.
5) F. Udrea and G. A. J. Amaratunga: IEEE Trans. Electron Devices **42** (1995) 1356.
6) N. Tokura: IEEJ Japan, EDD-96-103/SPC-96-83 (1996) 17 [in Japanese].
7) N. Yasuhara, H. Funaki, T. Matsudai and A. Nakagawa: Proc. Int. Symp. Power Semiconductor Devices & ICs (1996) p. 97.
8) M. Kitagawa and I. Omura: United States Patent, No. 5329142 (1994).
9) Alex Q.Huang: IEEE Electron Device Lett. **16** (1995) 408.
10) V. A. K. Temple: Proc. Power Conversion (1989) 544.