Proceedings of 1995 International Symposium on Power Semiconductor Devices & ICs, Yokohama 12.3

4500 V IEGTs having Switching Characteristics Superior to GTO

Mitsuhiko Kitagawa, Akio Nakagawa, Ken'ichi Matsushita, Shigeru Hasegawa,
Tomoki Inoue, Akihiro Yahata and Hiroshi Takenaka

Materials and Devices Labs., Research and Development Center
Toshiba Corporation
1, Komukai Toshiba-cho, Saiwai-ku, Kawasaki 210, Japan
Phone:+81-44-549-2138,Fax:+81-44-549-2259

ABSTRACT

In this paper, the authors report, for the first time, an exact prediction of the turn-off characteristics of 4500 V IEGTs and compare the results with those for GTOs. The prediction was made by means of device simulation and trial fabrication of IEGTs. The turn-off power loss of the 4500 V IEGT with a 17 μm deep trench gate is predicted to be less than that of the 4500 V GTO-thyristor. It was found that the IEGTs with 4 μm deep and wide trench gate can attain a small on-state voltage drop, which is the same level as that of the IEGT with 17 μm deep and narrow trench gate. The on-state voltage drop of the fabricated IEGT with the 4 μm deep trench gate is 4.5 V at 50 A/cm^2. Although the device design of the fabricated IEGT was not optimized, the observed turn-off characteristics were in good agreement with the simulated results. It has been numerically confirmed that the 4500V IEGT can realize a smaller turn-off loss than a 4500 V GTO-thyristor under a typical application circuit. It was, thus, confirmed that IEGTs can replace GTOs without degradation of switching frequency.

INTRODUCTION

GTO-thyristors with a 2500 to 6000 V forward blocking capability are widely employed in various power systems. However, one of the drawbacks of GTO-thyristors is the large gate current required to control them. Thus, it has been expected that GTOs will be replaced by MOS gate devices to simplify the gate circuits. 4500 V injection enhanced gate transistors (IEGTs) have been proposed as promising future high-voltage power devices that are capable of replacing GTO-thyristors[1-2]. Figure 1 shows a cross-sectional view of the simulated device of the 4500 V IEGT. In the figure, W is the source width (the trench gate to gate distance), D is a length of the high resistance n$^-$ channel region (a length that is the p-base width subtracted from the trench depth), and C is the unit cell size (a distance between the cathode contacts). It was demonstrated in [1] that, by optimizing the trench gate parameters, W, D and C, the IEGTs attain thyristor-like carrier distributions in the high resistance base layer, and realize almost the same low forward voltage drop as that of GTO-thyristors.

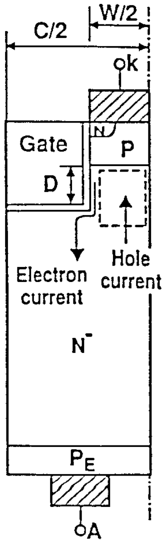

Fig. 1
Simulation model of IEGT

However, details of the electrical characteristics of 4500 V IEGTs have not yet been reported.

SIMULATIONS

a) Current-voltage Characteristics for IEGT

By using a 2-D device simulator TONADDE2C and 1-D analytical simulation model proposed at 1993 IEDM[1,2], the electrical characteristics of IEGTs were studied. The trench gate structural parameters of W, D and C for the simulated IEGTs are shown in Fig. 1. Figure 2 shows the calculated anode current density for the fixed anode voltage of 2.6 V as a function of the 5 μm wide trench depth, with all the other parameters being fixed: an emitter width W of 1 μm, the unit cell size C of 6 μm, the width of the high resistance base layer of 450 μm, and a carrier lifetime τ_H of 4 μsec. As the trench depth increases, the anode current density simply increases. However, the voltage drop along the trench MOS channel becomes large as the depth of the trench gate increases. It follows that the anode current density does not increase linearly but saturates as the trench depth increases.

Figure 3 shows the calculated anode current density for an anode voltage of 2.6 V as a function of unit cell size C, with all the other parameters being fixed: an emitter width W of 1 μm, the trench depth of 7 μm, the width of the high resistance base of 450 μm, and the carrier lifetime τ_H of 60 μsec. In the figure, as the trench width increases, anode current initially increases although the MOS channel density decreases. However, when the trench width becomes too large, the anode current begins to decrease because the voltage drop at the MOS channel becomes large.

By using the 1-D analytical simulation model, the on-state voltage drops of IEGTs were simulated as a function of the trench gate structural parameter of D and C. The calculated results are shown in Fig.4. The figure shows the calculated on-state voltage drop of an anode current density of 100 A/cm^2 as a function of unit cell size C and the trench depth of 3, 5 and 17 μm, with all the other parameters being fixed : an emitter width W of 1 μm, the width of p-base of 2 μm, the width of high resistance base layer of 600 μm, and a carrier lifetime τ_H of 10 μsec.

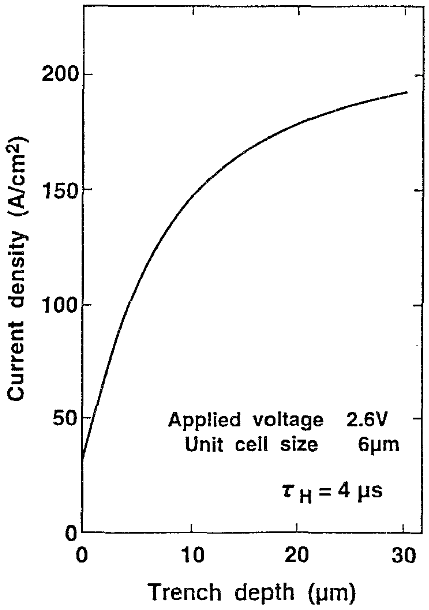

Fig. 2
Calculated anode current density for the trench depth

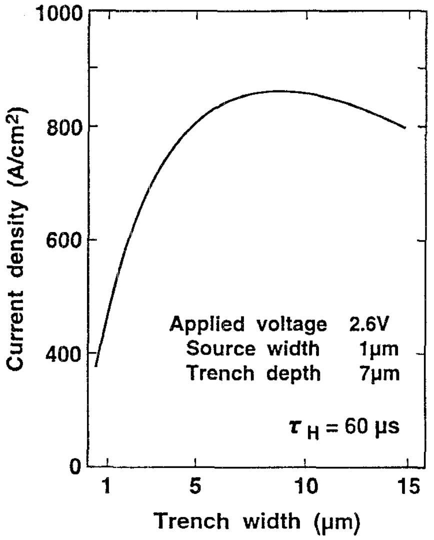

Fig. 3
Calculated anode current density for the unit cell size C

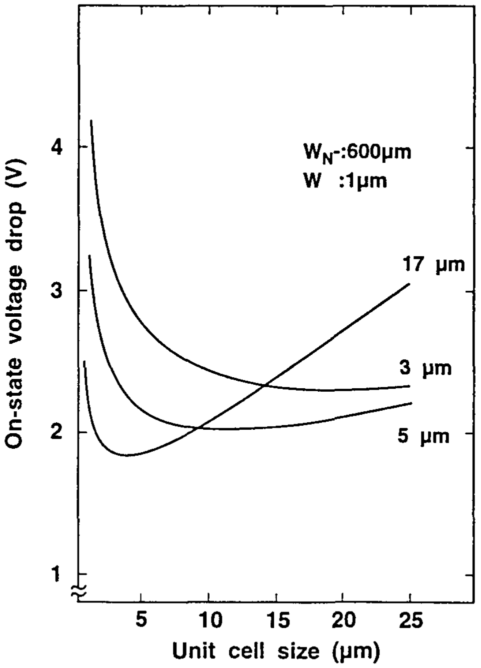

Fig. 4

Calculated on-state voltage drop for the cell size C with the trench depth D of 3, 5 and 17 μm

It was found that there are two trench gate design strategies for low forward voltage. One is deep and narrow trenches and the other is shallow and wide trenches.

b) Turn-off Characteristics

By using a 2-D device simulator TONADDE2C, the electrical characteristics of IEGTs and GTOs were compared. The structural parameters for the GTO were the same as those of a commercially available 4500V GTO with anode shorted structure. The comparisons were made between the IEGT and the GTO under the same on-state voltage drop and the same external circuit conditions. Figure 5 shows calculated forward current-voltage characteristics for IEGTs with 17 μm and 4 μm deep trench gates. Calculated current-voltage characteristics for the GTO are shown together for purposes of comparison. Figure 6 shows an electron density profile of the 4500 V IEGT with 17 μm deep trench gate.

The turn-off simulation was carried out taking into account the complete external circuit, including the snubber, and all the parasitics (see Fig.7)[3].

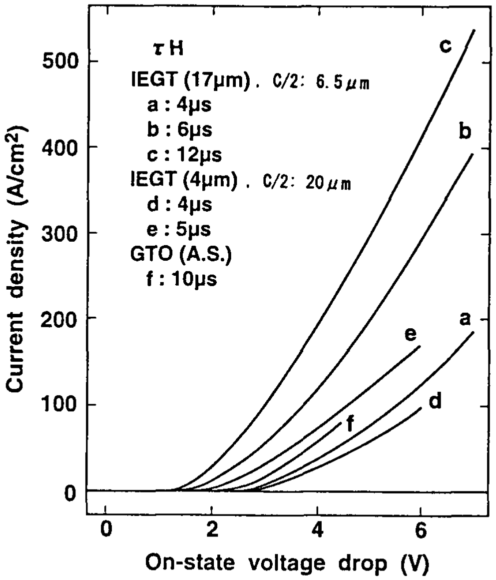

Fig.5

Calculated forward current-voltage characteristics for IEGT and GTO for various carrier lifetime of high resistance base layer

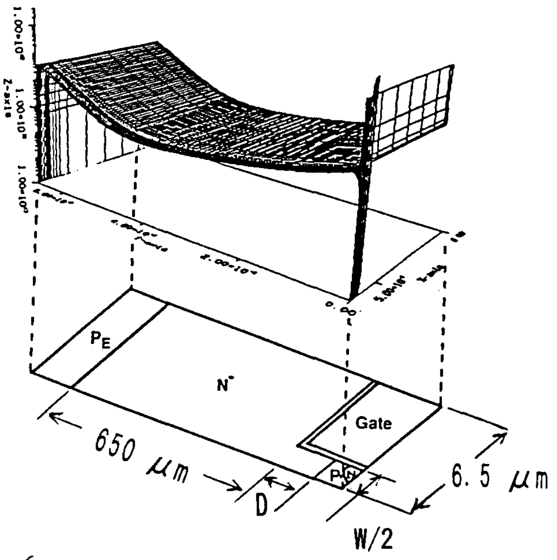

Fig. 6

Electron density profile of 4500 V IEGT during on-state and cross-sectional view of 4500 V IEGT

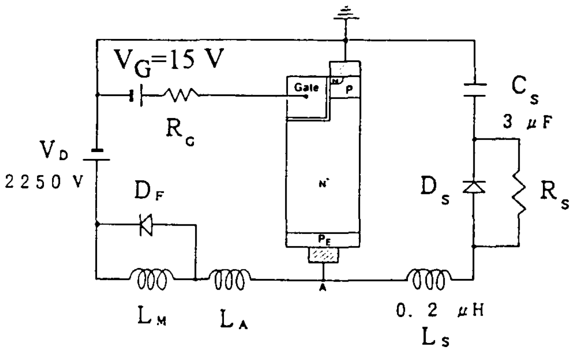

Fig. 7
External circuit for turn-off similation and all the parameters (at ITGQ=3000A) in the simulated system

Simulated IEGT turn-off waveforms are shown in Fig. 8. A detailed comparison of turn-off tail current between the simulated IEGT and GTO is shown in Fig. 9. The comparison was made for the devices with the same forward voltage drop and the same current density of 57 A/cm^2. It was found that the turn-off loss of the IEGT was smaller than that of the GTO.

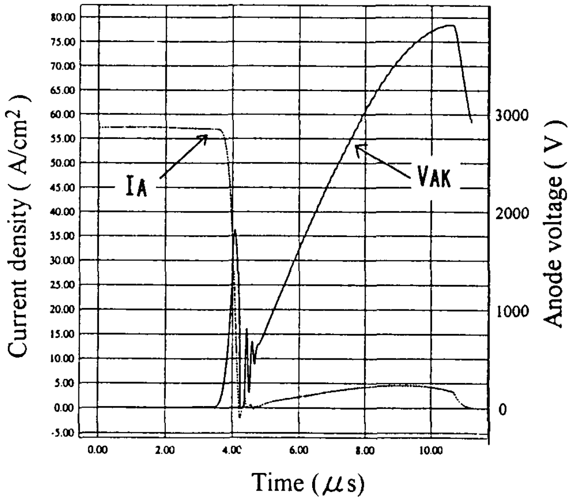

Fig. 8
Simulated IEGT turn-off waveforms

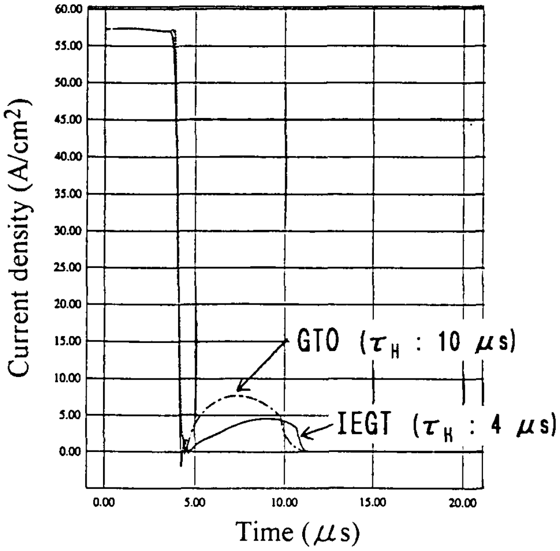

Fig. 9
Comparison of turn-off tail current of 4500 V IEGT and GTO during turn-off period

EXPERIMENTAL RESULTS

Figure 10 shows a cross-sectional view of the fabricated 4500 V IEGT with thinned-out cathode contacts. We define the thinned-out contact ratio, 1/n, as that the cathode metal contact window is made for every n-th trench-separated p-base. The IEGTs with trench depth of 4, 5 and 7 μm were fabricated and evaluated. The fabricated IEGTs have n-base of 600 μm, n-base resistance of 450 Ω-cm, and p-base thickness of 2 and 4 μm. The unit cell size C of 3 to 15 μm corresponds to the device with thinned-out contact ratio of 1/1 to 1/3. The active area of the IEGTs was 0.02 cm^2.

The forward blocking voltage of 4500V was obtained by the junction termination region of 1050 μm with a 800 μm p-type Resurf diffusion. The 4500 V forward blocking voltage waveform is shown in Fig. 11.

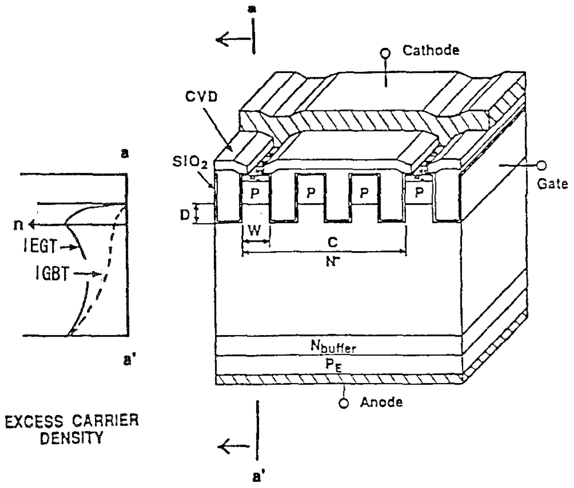

Fig. 10
Cross-sectional view of the fabricated 4500 V IEGT with thinned-out cathode contact ratio 1/3

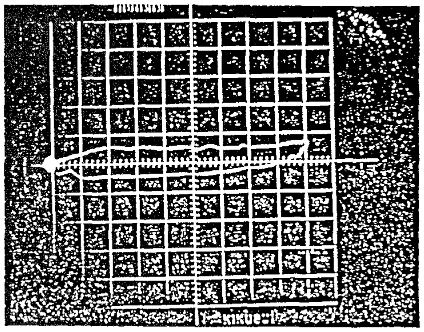

Fig. 11
4500 V Forward blocking waveform (500 V/div., 1 mV/div.)

a) Current-voltage Characteristics

Figure 12 shows the measured on-state voltage drop for the trench depth of 5 and 8 μm, as a function of the unit cell size, with all the other parameters being the same: an emitter width W of 2 μm, a width of high resistance base layer of 600 μm. The on-state voltage drops are measured at 75 A/cm^2 anode current density. As shown in the figure, the unit cell size corresponds to the ratio of thinned-out cathode contacts (from 1/1 to 1/3). A low on-state voltage drop was obtained for the fabricated IEGTs and there is a good agreement between the measured on-state voltage drops and the results calculated by using the 1-D analytical model (see Fig.4).

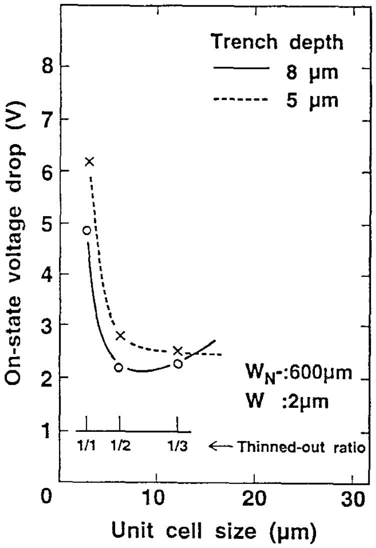

Fig. 12 Measured on-state voltage drop for the unit cell size (the ratio of thinned-out contacts) C

b) Turn-off loss vs On-state voltage drop

Figure 13 shows the measured resistive-load turn-off losses for the trench depth of 5 and 8 μm as a function of on-state voltage drop of 100 A/cm^2 anode current density, with the fixed parameters: an anode-cathode voltage of 1000 V, and an emitter width W of 2 μm. It is seen from Figs 12 and 13 that the IEGT with trench depth of 8 μm and the thinned-out ratio of 1/2 shows a better trade-off compared with that of the IEGT with trench depth of 5 μm and the thinned-out ratio of 1/1. Figure 14 shows experimentally obtained typical turn-off waveforms of a fabricated 4500 V IEGT with 4 μm deep trench gates, 2 μm deep p-base, and thinned-out cathode contact ratio of 1/4. The fabricated IEGT exhibited an on-state voltage drop of 4.5 V at 50 A/cm^2 and successfully turned off the anode current density of 100 A/cm^2.

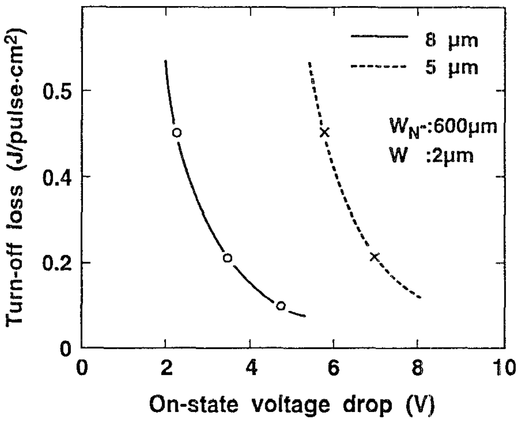

Fig. 13
Measured resistive-load turn-off losses of 4500 V IEGT for the on-state voltage

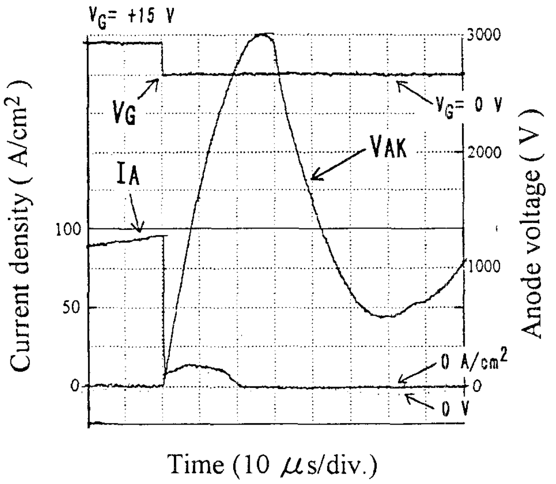

Fig. 14
Turn-off waveforms of fabricated 4500 V IEGT with a 4 μ m deep trench gate and thinned-out cathode contacts

Although the device design of the fabricated IEGT was not optimized, the observed turn-off characteristics were in reasonable agreement with the simulated results.

CONCLUSIONS

It has been confirmed that the 4500 V IEGT can realize a smaller turn-off loss than a 4500 V GTO-thyristor under the actual application system, retaining a high turn-off capability and easy gate drivability comparable to that of IGBTs. We anticipate that IEGTs will make an essential contribution to stable electric power networks by replacing GTO-thyristors.

ACKNOWLEDGMENTS

The authors are grateful to General Manager Makoto Azuma, Dr. Hiromichi Ohashi, Dr. Yasuo Ikawa, Mr. Minami Takeuchi, Dr. Masaru Nakamura and Mr. Tsuneo Ogura for their continuous interest in this work.

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