A 4500 V Injection Enhanced Insulated Gate Bipolar Transistor (IEGT) Operating in a Mode Similar to a Thyristor

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ABSTRACT

This paper proposes a new MOS-gate transistor structure (IEGT) for the first time, that realizes enhanced electron injection so that the carrier distribution takes a form similar to that of a thyristor and a low forward voltage drop is attained even for 4500 V devices.

A developed simple analytical one dimensional model can predict a sufficiently accurate current voltage curve and clarifies a new design criterion for IEGT operation.

A fabricated 4500 V IEGT realized a 2.5 V forward voltage drop at 100 A/cm². The IEGT had a current density over ten times that of the conventional trench gate IGBT at 2.5 V forward voltage drop.

An operation mode of IEGT has been theoretically and experimentally confirmed.

INTRODUCTION

IGBTs with a 600 to 1700 V forward blocking capability are applied widely in various power systems [1]. However, it has been believed that IGBTs with over 1700 V forward blocking capability have too large an on-state voltage drop compared with a GTO-thyristor.

As contrasted with GTO-thyristors, IGBTs basically operate in a mode similar to bipolar transistors, and thus have a low carrier accumulation in the n-type high resistance layer at the cathode side, suffering from a large forward voltage drop for over 2000 V devices. The MOS-controlled thyristor (MCT) represents an approach to the solution of this problem. However, the maximum anode current that can be turned off is limited by the shorting resistance of the MOS devices and the resultant current crowding [2].

This paper proposes a new MOS-gate transistor structure (IEGT) for the first time that realizes enhanced electron injection so that the carrier distribution takes a form similar to that of a thyristor and a low forward voltage drop is attained even for 4500 V devices.

DEVICE ANALYSIS

Fig. 1 shows the new structure, which is different from conventional trench gate IGBTs (UMOS-IGBTs) [3-6] in the sense that a new design criterion is imposed so that the hole current flow is suppressed by the deep trench gate geometry. Holes have to pass through a narrow n⁻ channel region surrounded by the deep trench gate walls to reach the p-base. In the narrow n⁻ channel region, holes have to flow only by diffusion and the amount of hole flow is restricted. In the n⁻ channel region, hole current J_h can be described by

$$J_h = 2kT\mu_h W(n_K/D)$$

Where W is the source width (the trench gate to gate distance), D is a depth of the n⁻ channel region (a distance from the bottom of the trench gate to the p-base), n_K is a carrier density at the cathode side of n-type high resistance layer and μ_h is a mobility of holes.

The device structural parameter (W/D) restricts the amount of hole current J_h. On the

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other hand, electron flow is not restricted by the geometry, because the electron current flows in the MOS-gate induced accumulation layer along the trench gate sidewalls. Thus, the injection efficiency of holes at the cathode side in the n-type high resistance layer can be described by

$$\Gamma_{h,K}=J_h/(JC)=2kT\mu_h\, n_K(W/DC)/J$$

$$J=(J_h+J_e)/C$$

Where C is a cell size and J is a total current density. The device structural parameter (W/DC) determines the injection efficiency. If (W/DC) is designed so that $(1-\Gamma_{h,K})$ is near unity, a thyristor-like carrier distribution is realized in the n-type high resistance layer, as seen in Fig. 1. I-V characteristics of an IEGT can be calculated with the injection efficiency of the anode p-emitter

$$\Gamma_{h,A}=1-\alpha_a n_A^2/J$$

and the continuity equation in the n-base layer

$$(dn^2/dx^2)=n/L_a^2$$

where α_a is a constant, L_a is an ambipolar diffusion length.

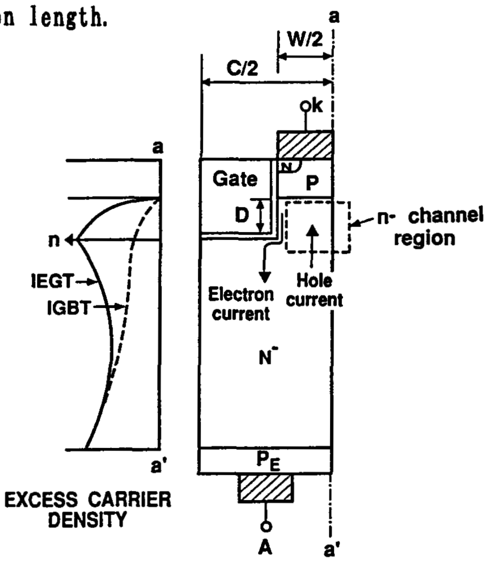

Fig. 1 Basic concept for IEGT device structure.

CALCULATIONS

Numerical simulations were carried out to verify the proposed concept. The calculated forward I-V characteristics of a 4500 V IEGT are shown in Fig. 2. In the figure, a comparison is made between the on-state voltage drops of an IEGT, a third generation planar gate 4500 V IGBT and a 4500 V GTO-thyristor. It has been confirmed that the IEGT attains a low forward voltage drop closely equivalent to that of a GTO-thyristor. The on-state voltage drop of the IEGT is further improved by reducing the device structural parameter W, as seen in Fig. 3.

A simple analytical one-dimensional model that mentioned above can predict a sufficiently accurate current voltage curve (see Fig. 2) and clarifies a new design criterion for IEGT operation.

Fig. 4 shows the calculated turn-off waveforms for an optimized IEGT under the resistive load. The applied voltage is 1000 V and turn-off current density is 5470 A/cm². Turn-off time is less than 200 ns. It has been confirmed that a current turn-off capability as large as that of conventional IGBTs is retained.

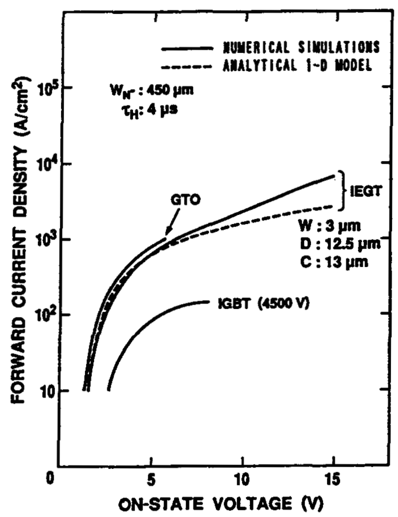

Fig. 2 Calculated I-V characteristics of IEGT, GTO, IGBT with same blocking capability of 4500 V. IEGT has the same low on-state voltage drop as a GTO.

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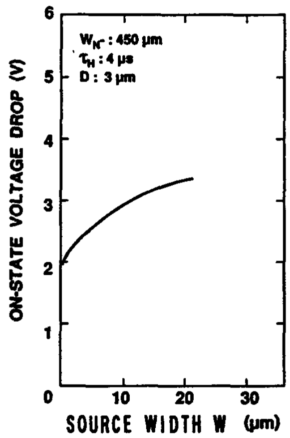

Fig. 3 On-state voltage drop becomes smaller as the source width W (see Fig. 1 for the definition of W) of the IEGT decreases.

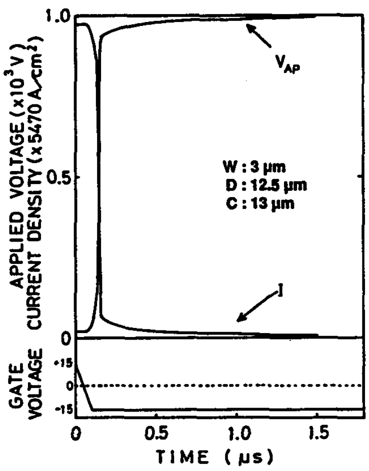

Fig. 4 Calculated turn-off waveforms of IEGT.

DEVICE FABRICATION

Based on the above analyses, 4500 V IEGTs have been fabricated and evaluated. The authors adopted a practical alternative gate structure as shown in Fig. 5. In the structure, multiple trenches filled with p-base diffusions were adopted as alternatives equivalent to the wide trench gates. IEGTs and conventional UMOS-IGBTs have been fabricated in the same wafer. The device size was 0.02 mm^2 with unit cells of 3 to 30 μm. Forward blocking capability was 4500 V. The lightly doped n-base was 450 Ω-cm and 600 μm thick. The minimum trench width and the minimum trench gate to gate distance were 1 and 2 μm respectively. The trench depths were 5 to 9 μm. A 4 μm deep p-type base layer was formed by boron diffusion. A 30 μm thick n-type buffer layer was formed by phosphorus diffusion. An aluminum electrode was formed on the n-source and the p-base. A vanadium-nickel-gold trimetal system was formed on the p-emitter. Figure 6 is an investigated IEGT chip.

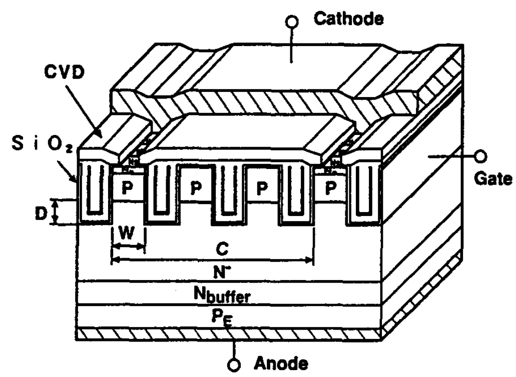

Fig. 5 The fabricated IEGT structure.

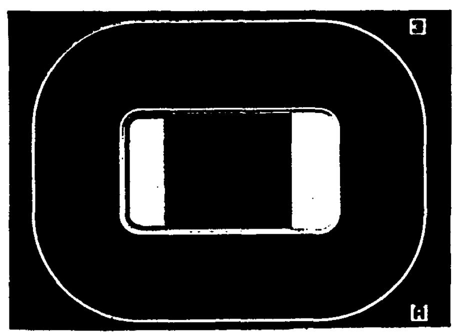

Fig. 6 Photograph of fabricated IEGT. Chip size is 4 × 5 mm^2.

DEVICE CHARACTERISTICS AND DISCUSSIONS

Fig. 7 shows the experimental results. The MOS-channel density of the fabricated IEGT was one tenth that of the fabricated conventional trench gate IGBT. However, the 4500 V IEGT realized a 2.5 V forward voltage drop at 100 A/cm^2, which was far better than a 6.0 V forward voltage drop at the same forward current density of the conventional UMOS-IGBT. The IEGT had a current density over ten times that of the conventional UMOS-IGBT at 2.5 V forward voltage drop. This result means that the voltage drop at the n-type high resistance layer dominates the on-state voltage of the devices, rather than a voltage drop at the MOS channel.

The forward conduction characteristics of the IEGT are compared with the conventional UMOS-IGBT in Fig 7. A good agreement was obtained between the calculated values and the measured values for IEGT, verifying the validity of the proposed concept.

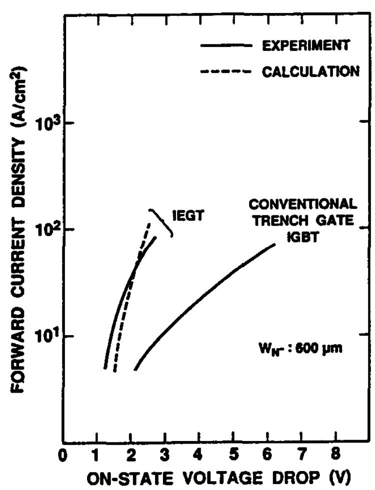

Fig. 7 Experimentally obtained current voltage curves for on-state voltage (experiment and calculation)

CONCLUSION

The authors have proposed a new MOS-gate transistor structure (IEGT) for the first time, that realizes enhanced electron injection so that the carrier distribution takes a form similar to that of a thyristor. A low forward voltage drop was attained even for 4500 V devices.

Numerical simulations were carried out to verify the proposed concept. A simple analytical 1-d model has been developed to analyze the operation mechanism of the IEGT. The developed 1-d model can predict a sufficiently accurate current voltage curve and clarifies a new design criterion for IEGT operation.

A fabricated 4500 V IEGT with multiple trench gates exhibited a 2.5 V forward voltage drop at 100 A/cm^2 , which was far better than conventional 4500 V UMOS-IGBTs. The current density of IEGT at 2.5 V forward voltage drop was over ten times as large as that of the conventional UMOS-IGBT.

It was also confirmed that the IEGT can realize a low on-state resistance just like a GTO-thyristor, while retaining the same high turn-off capability and easy gate drivability as an IGBT.

IEGTs are promising candidates for future high-voltage high-power devices and have the potential to replace GTO-tyristors.

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