IGBT Mode Turn-Off Thyristor (IGTT) Fabricated on SOI Substrate

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ABSTRACT

A new lateral MOS-gated thyristor, called an IGBT mode turn-off thyristor (IGTT), fabricated on an SOI substrate is proposed. A maximum turn-off current of more than 150 A/cm^2, which is 10 times larger than that of a conventional MOS-gated thyristor, has been realized. A homogeneous current distribution at the turn-off stage and a low shorting resistance between the p-base layer and the cathode attained by the IGTT are assumed to increase the maximum turn-off capability. The forward voltage drop in the IGTT is much smaller than that of an IGBT with an approximately equivalent turn-off time.

INTRODUCTION

In recent years, MOS-gated power semiconductor devices, such as a power MOSFET [1] and IGBT [2][3], have become increasingly important because of their high input gate impedance for use in power integrated circuits (PICs) [4]. Furthermore, in order to broaden the application range of PICs, it is required to reduce the chip size by implementing a thyristor with low on-state voltage characteristics. However, the performance of the thyristor operating beyond the latch-up point is limited by two main drawbacks. Those are a low maximum turn-off current caused by current filamentation and a long turn-off time due to a large amount of stored carriers at the forward conduction stage [5].

The purpose of this paper is to propose a new lateral MOS-gated thyristor, called an IGBT mode turn-off thyristor (IGTT), fabricated on an SOI substrate to overcome these difficulties. The feature of the IGTT is a combination of a novel integrated structure for the MOSFET which shorts emitter-base junction and an IGBT mode turn-off mechanism. This paper describes an experimentally demonstrated IGTT having a superior turn-off current capability to that of the conventional MOS-gated thyistor. It also reports on the result that this IGTT offers a better trade-off relation between the forward voltage drop and the turn-off fall time when compared with the IGBT.

DEVICE STRUCTURE

The maximum turn-off current capability for a MOS-gated thyristor strongly depends on the shorting resistance between the p-base layer and the cathode [6]. It is, therefore, important to reduce the shorting resistance to improve the maximum turn-off current capability . The IGTT realizes a lower shorting resistance compared to the conventional MOS-gated thyristor with the same design rule. The device structure consisting of a 500-V MOS-triggered thyristor and a low voltage n-channel MOSFET are shown in Fig. 1. A floating metal (S) connecting the p-base layer of the thyristor and the drain layer of the n-channel MOSFET are formed at a position adjacent to the n-emitter layer to effectively sweep away stored carriers at the turn-off stage, which is a unique feature of the IGTT.

The first order approximation of the maximum turn-off current I_{TGQM} for the MOS-gated thyristor is given by

$$I_{TGQM} = Vj \ / \ (\alpha_{PNP} \cdot R_S) \qquad (1)$$

where Vj is the maximum voltage to maintain the n-emitter/p-base junction forward biased, α_{PNP} is the current gain of the pnp transistor, and R_S is the shorting resistance. The shorting resistance of the IGTT (R_{SI}) is described by

$$R_{SI} = R_{P1} + R_{MOS} \qquad (2)$$

and the shorting resistance of a conventional MOS-gated thyristor (R_{SC}), shown in Fig.2, is also described by

$$R_{SC} = R_{P1} + R_{P2} + R_{MOS} \qquad (3)$$

where R_{P1} and R_{P2} are the resistances of the p-base layer below the n-emitter and n-drain layers, respectively. R_{MOS} is the on-resistance of the low voltage n-channel MOSFET. It is clear that the novel NMOS configuration achieved by the IGTT eliminates the parastic

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resistance, R_{P2}, resulting in a small shorting resistance.

Furthermore, the NMOS channel resistance is reduced by introducing an interdigitated NMOS configuration to broaden the channel width, as shown in Fig.3. The simple n-emitter structure of the IGTT can also easily decrease R_{P1} by reducing the n-emitter length. These advantages of the IGTT improve the turn-off capability, as described in the next section.

TURN-OFF CHARACTERISTICS

The MOS-gated thyristor with double gates are turned off by two different turn-off triggering methods. One of the methods is the conventional GTO turn-off operation at which the turn-off gate (G_{OFF}) is positively biased after removing the turn-on gate bias (G_{ON}), as shown in Fig.4 (a). Another turn-off mode is applying a positive bias to the turn-off gate before removing the turn-on gate pulse. After triggering the turn-off gate, the on-state voltage rapidly increases, exhibiting a transformation from the thyristor mode to the IGBT mode, as shown in Fig. 4(b).

The maximum turn-off current was greatly increased by applying the new turn-off mechanism, the IGBT mode turn-off operation, to the new device structure [7]. The I_{TGQM} dependence on the shorting resistance, R_S, is shown in Fig. 5. Two shorting resistance cases of 12 ohms and 4 ohms, corresponding to the basic and interdigitated MOS structures for IGTT, are shown in this figure. The I_{TGQM} value for the conventional MOS-gated thyristor operating at GTO turn-off mode is also shown in this figure. The I_{TGQM} for IGTT increases in inverse proportion to the shorting resistance. It is clearly seen that more than 150 A/cm^2 of I_{TGQM}, which is 10 times larger than that of the conventional MOS-gated thyristor, was realized by IGTT. To the contrary, the I_{TGQM} value for the MOS-gated thyristor with the same device structure as IGTT operating by the GTO turn-off mode increases but remains less than 60 A/cm^2. It can be assumed that a homogeneous current distribution at the turn-off stage and the low shorting resistance attained by the IGTT increases the maximum turn-off current capability.

TRADE-OFF RELATION

A trade-off relation between the forward voltage drop and the turn-off fall time was greatly improved by the IGTT fabricated on an SOI substrate. It is evident from Fig. 6 that the forward voltage drop in the IGTT is close to that of a diode and much smaller than that of the IGBT. Figure 7 shows the turn-off waveforms for the IGBT with the same n-emitter width as that of the IGTT. This IGBT was fabricated by the same process sequence and design rule as the IGTT to compare them precisely. It can be seen that the turn-off fall time of the IGBT is approximately equal to that of the IGTT illustrated in Fig.4(b). It can be assumed that a thin active layer SOI structure approximately 25 μm thick realizes this short fall time for the IGTT. Figure 8 shows the trade-off relation between the turn-off fall time and the forward voltage drop at 150 A/cm^2 for the IGTT and the IGBT. The time taken for the anode current to fall from 90 % to 10 % of its on-state value was defined as the turn-off fall time. It is evident that the forward voltage drop in the IGTT is much smaller than the corresponding value for IGBT with an approximately equivalent turn-off fall time.

CONCLUSION

A new MOS-gated thyristor called the IGBT mode turn-off thyristor has been described. The device has been designed and is operated so as to change from the latched-up forward conduction mode to the unlatched forward conduction one, using a MOS gate. The concept of the device and IGBT mode turn-off operation has been verified by experimental measurements on devices fabricated using the IGBT process. The excellent turn-off current capability and forward conduction characteristics indicate a high potential for various applications.

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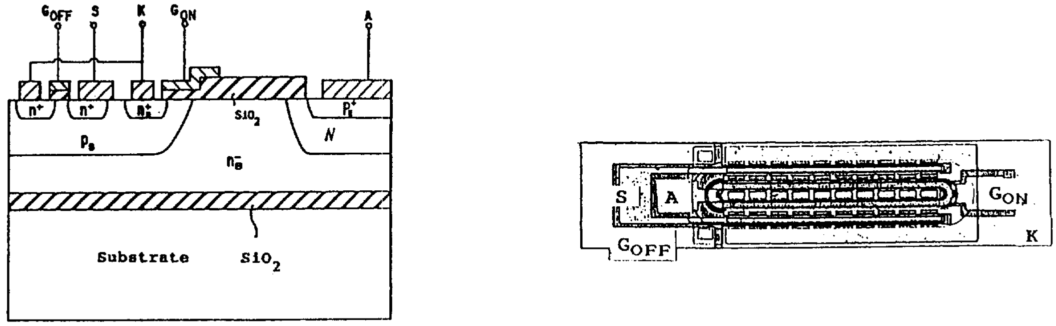
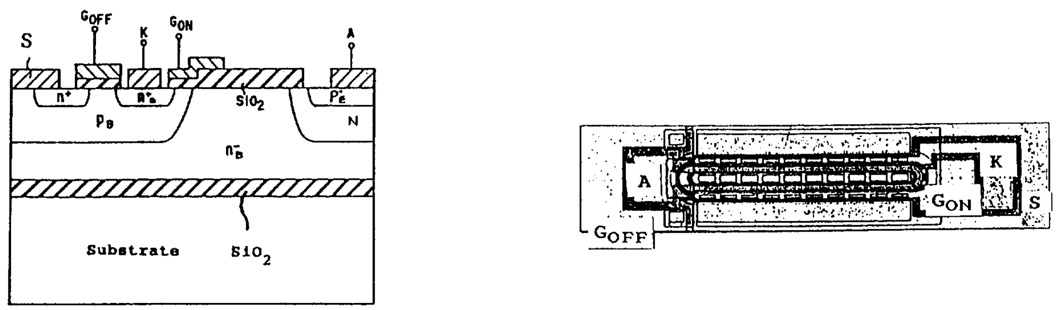


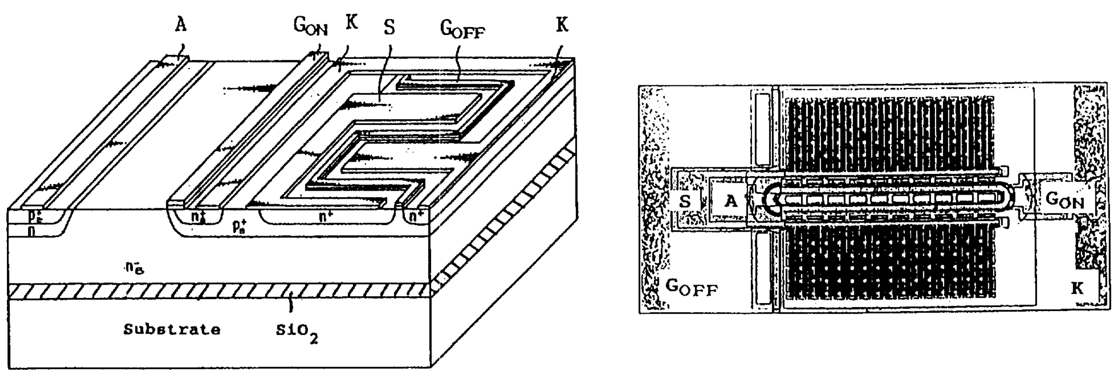
(a) (b)

Fig.1 (a) cross-sectional view and (b) photo of IGTT fabricated on SOI substrate



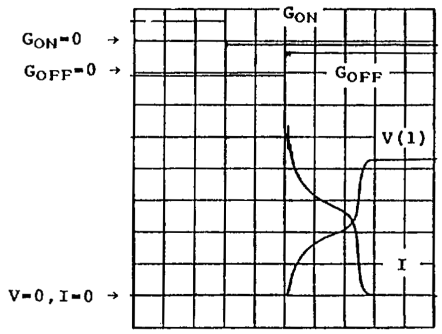
(a) (b)

Fig.2 (a) cross-sectional view and (b) photo of conventional MOS-gated thyristor fabricated on SOI substrate

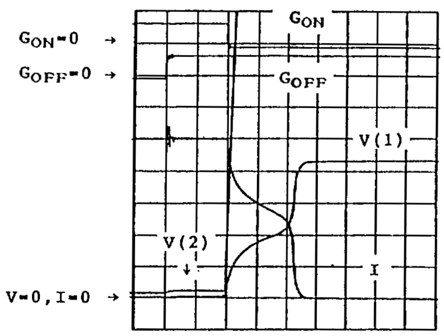


(a) (b)

Fig.3 (a) cross-sectional view and (b) photo of IGTT with interdigitated MOSFET fabricated on SOI substrate



(a) GTO mode turn-off



G_{ON} : 20 V/div. V(1) : 50 V/div.
G_{OFF} : 20 V/div. V(2) : 5 V/div.
t : 1 μs/div. I : 20 mA/div.

(b) IGBT mode turn-off

Fig.4 Turn-off waveforms for IGTT

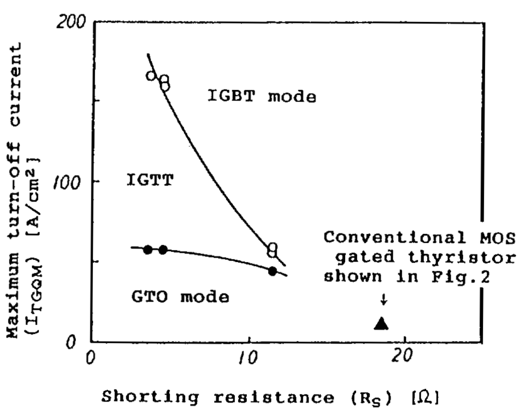


Fig.5 Maximum turn-off current (I_{TGQM}) dependence on shorting resistance (R_S) for IGTT and conventional MOS-gated thyristor

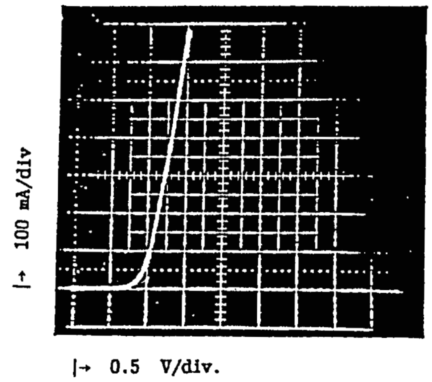
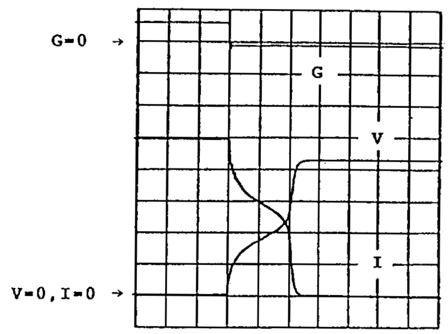


Fig.6 I-V characteristics of IGTT



G : 20 V/div. V : 50 V/div.
t : 1 μs/div. I : 20 mA/div.

Fig.7 Turn-off waveforms for IGBT with the same n-emitter width as IGTT

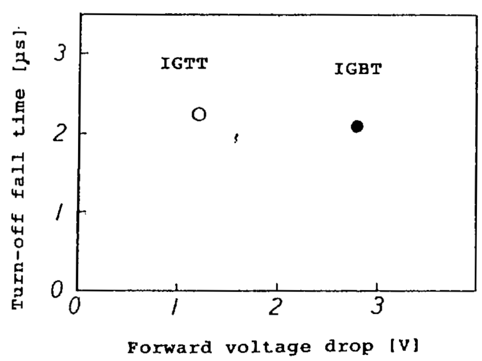


Fig.8 Trade-off relation between forward voltage drop and turn-off fall time for IGTT and IGBT