Perspective Performances of MOS-Gated GTO in High Power Applications

Cesare Ronsisvalle, Vincenzo Enea, Carmine Abbate, Giovanni Busatto, Annunziata Sanseverino

Abstract— In this paper we present the experimental and simulated characteristics of a new power semiconductor device, named MOS-GTO, for high power applications. The results are presented for a 1.2kV device and subsequently scaled up to 4.5kV blocking voltage. The excellent on-state voltage and switching characteristics make MOS-GTO a very promising device for high voltage power applications.

***Index Terms*—Power semiconductor devices.**

I. Introduction

IGBTs devices are widely used in power conversion but their performances are limited in high voltage applications because the conductivity modulation of the n- base present in their vertical structure is sustained only by the collector junction. As a consequence for devices with blocking voltages larger than 3kV the required wide n-base thicknesses causes the on-state voltage drop to become relatively high. To overcome this limitation, in the last years, many structures has been proposed. Devices like IEGT [1], HIGT [2] and SPT+ [3] which enhanced the physical characteristics of IGBTs, have been developed to obtain a more thyristor like conductivity modulation profile thus obtaining improved on-state characteristics that however are far to be completely comparable with those ones of a true thyristor.

Other devices like EST [4] and MCT [5] base their operation on the activation of a main thyristor into their vertical structure for which both anode and cathode junctions contribute to the conductivity modulation. These devices, though, are affected by the presence of parasitic thyristors that can latch up in static and dynamic operations limiting the safe operating area of the device. More recently CIGBT [6] has been presented which overcomes thyristor parasitic problem thanks to internal structure formed by clustering power MOSFET cathode cells within common n and p wells, showing very interesting characteristics. However this device presents the main thyristor fabricated by a triple diffusion which guarantees a very poor cathode efficiency.

Recently the principle of operation of a functionally integrated monolithic MOS-Gated thyristor [7] (MOS-GTO)

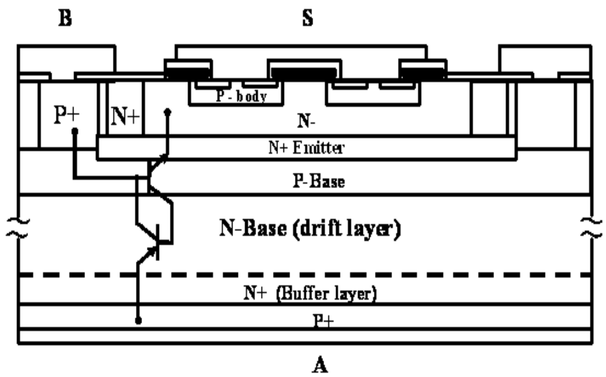

Fig.1. Schematic of the elementary cell of the proposed device.

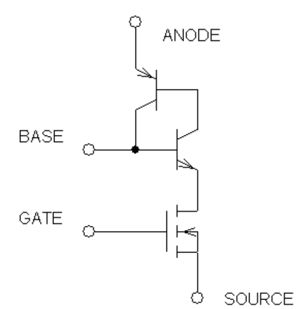

Fig.2. Equivalent circuit of the proposed device.

has been presented as an evolution of the Emitter Switched Bipolar Transistor [8]. This device combines the advantage of a gate turn-off thyristor with an easy MOS gate control without the presence of latching parasitic devices. Similar Emitter Switched Thyristor structures (ETO) were also presented in a discrete form and showed very interesting performances [9].

Due to the latching nature of these devices, the basic performances appear to be particularly interesting in high voltage applications where the large on state voltage drop across the device becomes a serious problem that increases its power dissipation and limits the converter efficiency.

The objective of this paper is to present the perspective performances of the fully integrated MOS-Gated GTO in the range of high blocking voltages. We start from the characteristics of an experimentally fabricated 1.2kV device, that we used also to tune the simulation models, and we extend the analysis up to 4.5kV blocking voltage. The simulated characteristics of high voltage MOS-Gated GTOs

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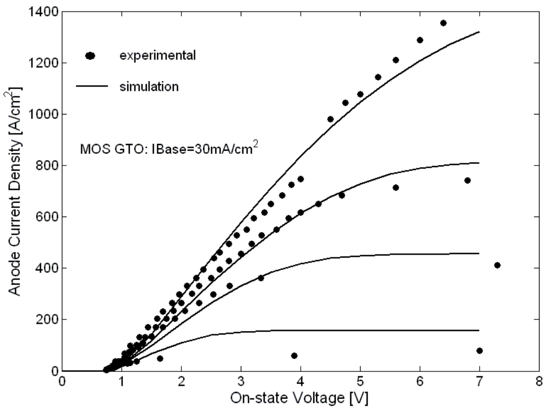


Fig.3. Experimental and simulated forward characteristics of 1.2kV device varying the gate voltage. For the simulated device the N^-drift region lifetimes are fixed to τ_{no}=10us and τ_{po}=3us.

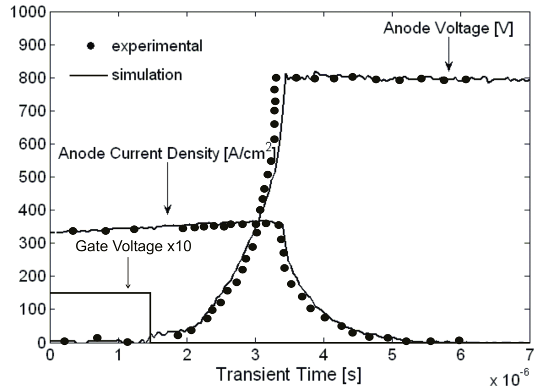


Fig.4. Experimental and simulated turn-off waveforms of 1.2kV MOS-GTO.

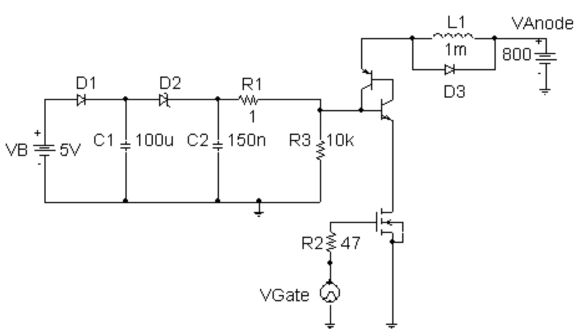
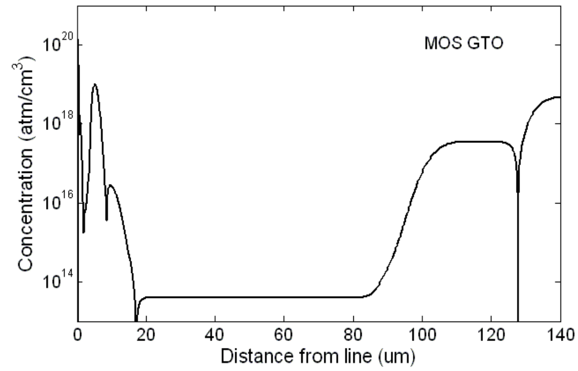
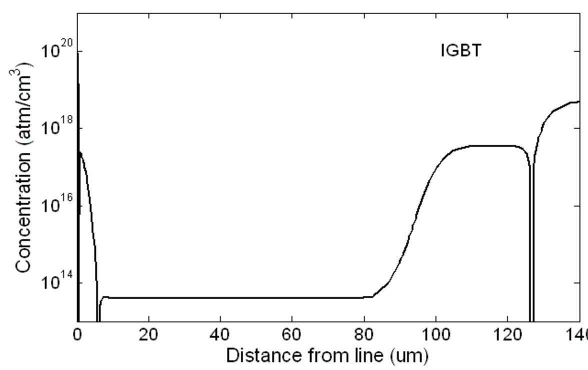


Fig.5. Circuit used for the turn-off commutations.



a)



b)

Fig.6 Doping profile of simulated a) 1.2kV MOS-GTO, b) 1.2kV IGBT.

with different blocking voltage are compared with those of IGBTs at same stage of development.

II MOS-GTO OPERATION

In Fig.1 the structure of the MOS-GTO elementary cell is presented. The structure is achieved by integrating low voltage MOS cells inside the cathode region of a high voltage gate turn-off thyristor.

The equivalent circuit of the cell is depicted in Fig.2 that clearly shows the thyristor cathode in series with a N-channel MOSFET. When the MOSFET is on, the device is similar to a thyristor and the current flows from the anode to the cathode. When the MOSFET is switched off, the cathode current is immediately cut off and the anode current is diverted to the base terminal so that the GTO is turned off with a unity turn-off current gain.

Based on the outcome of Silvaco TCAD-Atlas mixed mode simulations [10], 1.2kV voltage rated prototypes, having an area of about 23mm^2, have been fabricated. The experimental and simulated forward characteristics of a device irradiated with 15MRad electron dose are displayed in Fig.3 at increasing gate voltage and fixed base current of about 30mA/cm^2.

The experimental and simulated inductive turn off waveforms for the 1.2kV MOS-GTO are reported in Fig.4 and the related test circuit is reported in Fig.5.

IIISIMULATIONS

To better highlight the capabilities of the proposed device at increasing values of the blocking voltage, we have compared the forward and switching simulated characteristics of the MOS-Gated-GTOs with those of first generation IGBTs having the same $n^-n^+p^+$ vertical structures.

It is worth outlining that the resulting IGBT used for the comparison is not optimized and can be considered as a first generation device. In the years the IGBT performances have been significantly improved by introducing several technological modifications, (like light emitter, local lifetime control etc.). Nevertheless we prefer to compare the performance of the newly proposed device with those of an IGBT at the same stage of development in consideration that

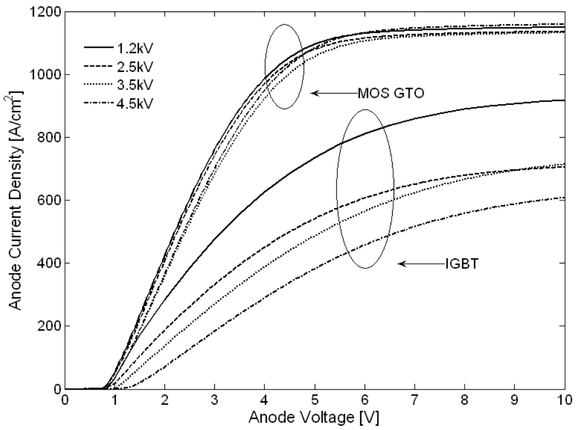


Fig.7. Comparison between the on state characteristics of MOS-GTO and IGBT devices having different blocking voltage.

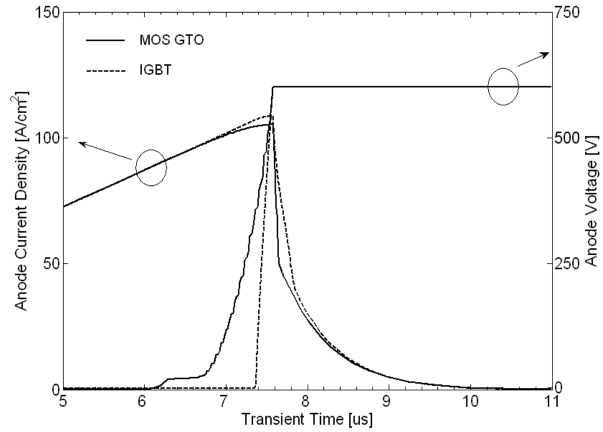


Fig.8 Turn-off waveforms of 1.2kV MOS-GTO and IGBT for a commutated anode current density of about 100A/cm^2.

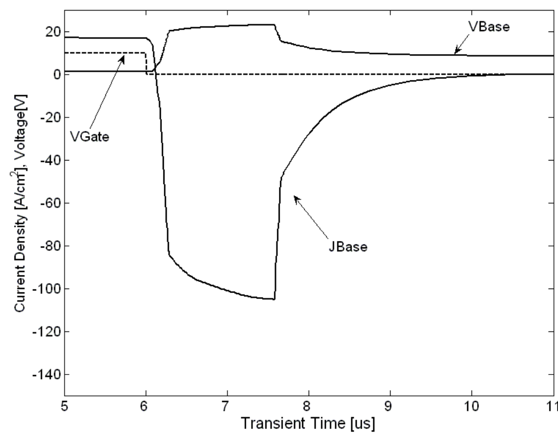


Fig.9 Base current density, base voltage and gate voltage progress during the turn off of 1.2kV MOS-GTO .

practically all technological improvements achieved on the IGBT can be also exported to the MOS-Gated GTO. Therefore we strongly believe that the results of the following analysis can give useful highlights about the perspective potentiality of the proposed device with respect to the existing technologies.

Starting from the physical structure of the constructed 1.2kV prototype, the doping profiles used to simulate 1.2kV MOS-GTO and IGBT devices was obtained. Successively the doping and width of the n-base were adjusted to achieve devices with a desired blocking voltage. For both simulated devices we have considered a reference n-drift lifetime of 30us for electron and 10us for holes. In Fig.6 a) and b) the net doping profiles along the structures are reported starting from the source contact, for both 1.2kV devices.

A comparison between the on-state characteristics of both MOS-GTO and IGBT are reported in Fig.7 for different blocking voltages and V_{GATE}=10V. The figure shows that the on-state voltage drop of the IGBT increases with the blocking voltage, whereas the MOS-GTO exhibits characteristics almost independent of the variation of the base physical parameters: the activation of the internal thyristor of MOS-GTO drastically reduces the on state voltage drop during the conduction phase.

Let us compare the switching performances of the two devices. A first simulation result is reported in Fig.8 where the turn off waveforms are reported for MOS-GTO and IGBT rated at 1.2kV. The test circuit is the similar to that used for the experiment of Fig.5. The duration of the on-state for both devices was set to reach an anode current density, J_A, of about 100A/cm^2 at the onset of the current fall.

If we focus the attention on the turn-off waveforms of MOS-GTO reported in Fig. 8 and 9 we can see some peculiarities of the MOS-Gated GTO inductive turn-off. After the turn-off of the internal MOSFET, which takes place when its gate voltage is turned to zero, the device experiences a storage phase during which the anode voltage increases and reaches a plateau value which is imposed by the external circuit (see Fig.8 between 6.3us and 7us). At the end of the storage phase the anode voltage continues up to the power supply voltage, the turn off is completed by the anode current fall down and the subsequent tailing phase.

On the gate side, during the storage phase the thyristors anode current flows totally in the base circuit (see Fig.9 between 6.3us and 7.7us) while the base voltage is fixed by the voltage drops across the capacitor C_2 and the resistor R_1 which are selected to keep this voltage below the breakdown of the internal MOSFET. The Zener-Diode D_2 helps in this goal because when it starts to conduct a significant part of current is diverted to the larger capacitor C_1. After the storage completion the base current evolution follows the anode current fall down has it happens in the emitter switched cascode structures.

If we compare the output switching waveforms of MOS-GTO and IGBT we can see that due to the higher charge stored in its base the MOS-GTO turn-off is slower than the IGBT both during the voltage rise and the current fall so that the calculated turn-off energies are 42.7mJ and 35.9mJ, respectively. On the other hand the on state voltage drops for the two devices are 1.13V and 1.23V, respectively.

The results of Fig.8 indicate that the larger turn-off energy associated to the MOS-GTO is compensated by a lower on-state voltage drop. For a good comparison between the two devices we have to consider the trade-off between their static and dynamic characteristics.

The simulated trade-off curves are reported of Fig.10. Each curve reports the on-state voltage drop (V_{ON}) on the abscissas

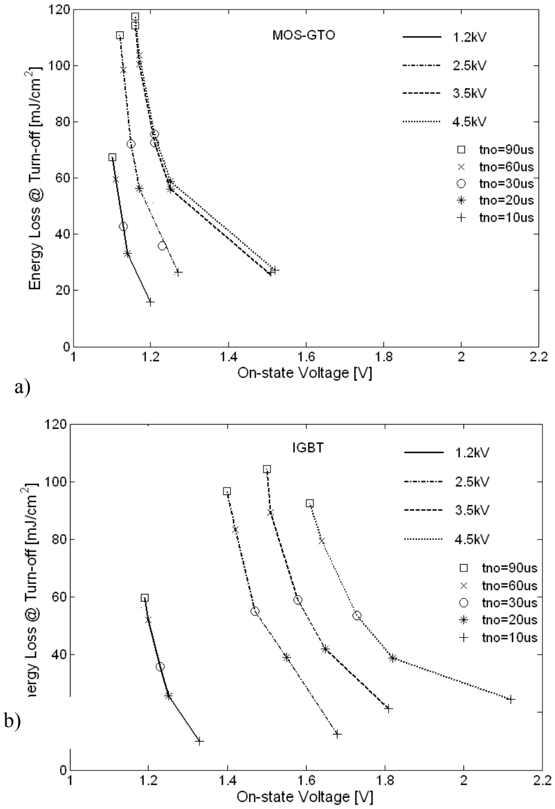


Fig.10 Trade-off curves of a) MOS-GTO and b) IGBT devices with different blocking voltage at J_A=100A/cm^2. The curves are obtained for different value of N-drift region lifetime with tpo=tno/3.

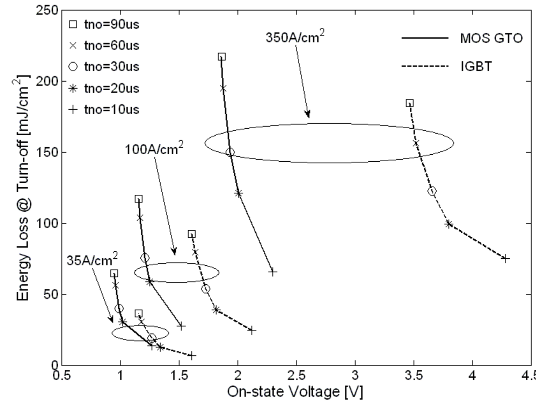


Fig.11 Comparison of trade-off curves for 4.5kV devices at different commutated anode current density J_A.

and the turn-off energy losses (E_{OFF}) on the ordinates. The two groups of curves reported for the MOS-GTO (Fig.10a) and the IGBT (Fig.10b) refer to four values of the blocking voltages. Each curve was obtained by using different values of the lifetime.

For each value of the blocking voltage the trade-off curve of the MOS-GTO is below the corresponding one of the IGBT. That is a proper choice of the lifetime allows us to obtain a MOS-GTO with an assigned V_{ON} having a lower E_{OFF} than the corresponding IGBT or, vice versa, an assigned E_{OFF} with a lower V_{ON}.

The absolute distance between the trade-off curves of the two devices having the same blocking voltage increases with the blocking voltage. In particular, the curve of the 4.5kV IGBT shows a V_{ON} increased by 0.42V (35%) at E_{OFF}=92mJ with respect to the MOS-GTO and by 0.52V (34.5%) at E_{OFF}=28mJ. This relevant variation of the V_{ON} is particularly valuable in high power application where the switching frequencies used are typically quite low and the larger part of the power dissipation is due to the conduction losses.

The advantages arising from the use of the MOS-GTO for high voltage applications are much more evident at increasing anode current densities as it is shown in Fig11 where the trade-off curves are reported for 4.5kV devices at different J_A values. This characteristic is particularly valuable for high power applications because it permits to increase significantly the current capabilities of the power device.

IV CONCLUSION

A simulation study regarding the expected performances of high voltage MOS-GTO devices has been presented. The static and dynamic characteristics for different blocking voltages have been compared to those of corresponding first generation IGBT. Simulation results indicate that the proposed devices can be considered to be a good competitor of IGBT devices particularly for high voltage high power applications.

REFERENCES

[1] M. Kitigawa, I. Omura, S. Hasegawa, A. Nakagawa, " A 4500V injection Thyristor", IEEE IEDM tech. digest, pp.679, 682, 1993.

[2] M. Mori, Y. Uchino, J. Sakano, H. Kobayashi, "A Novel High-Conductivity IGBT (HiGT) with a Short Circuit Capability", Proceeding of 1998 International Symposium on Power Semiconductor Devices & ICs, Kyoto.

[3] M. Rahimo, A. Kopata, S. Eicher; "Next Generation Planar IGBTs with SPT+"; *Power Electronics Europe*, Issue 06, 2005.

[4] M.S. Shekar, B.J. Baliga, M. Nandakumar, S.Tandon, A.Reisman, "Characteristics of the Emitter-Switched Thyristor", IEEE Transaction on Electron Devices, vol.38, no.7,July 1991, pp. 1619 - 1623.

[5] V.A.K. Temple," MOS-Controlled Thyristor – A new class of power devices", IEEE Transaction on Electron Devices, vol.33, no.10, 1986, pp. 1609-1618.

[6] E.M. Sankara Narayanan, M.R. Sweet, N. Luther-King, K. Vershinin, O. Spulber, M.M. De Souza, J.V. Subhas Chandra Bose, " A Novel, Clustered Insulated Gate Bipolar Transistor for High Power Applications", Semiconductor Conference 2000.

[7] C.Ronsisvalle, V.Enea, G, Belverde," A Novel MOS_gated Thyristor 4-Terminal Device particularly suited for High-Current and High-Frequency Applications", 9th International Seminar on Power Semiconductor, Prague 2008.

[8] C.Ronsisvalle, V.Enea: The ESBT," a new monolithic power actuator technology devoted to high voltage and high frequency applications", CIPS'08, Nuremberg, 2008.

[9] B.Chen, A. Q. Huang, M. Baran, C. Han, W. Song, "Operation characteristics of emitter turn-off thyristor (ETO) for solid-state circuit breaker and fault current limiter", 21st Annual IEEE Applied Power Electronics Conference and Exposition, 2006. APEC '06. 19-23 March 2006. pp. 174-178.

[10] SILVACO International. "ATLAS user's manual: Device simulation software", vols.1 and 2. SILVACO International, 4701 Patrick Henry Drive, Bldg.1, Santa Clara, CA 95054.