The Uniform Turn-on of the Emitter Turn-Off Thyristor

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***Abstract*- The emitter turn-off (ETO) thyristor is a new MOS-controlled thyristor that is suitable for use in high-power converters due to its improved switching performance and easy control. This paper analyzes the uniform turn-on process of the ETO for the first time. To achieve uniform turn-on, the required gate current amplitude and rise rate are characterized for different ETO prototypes. Experimental results show that the ETOs can be uniformly turned on. Correspondingly, the maximum anode current rise rate is improved and the minimum on-time is reduced.**

I. INTRODUCTION

Due to the emergence of advanced power semiconductor devices, power conversion technology developed very fast in the past decade. High-power converters are increasingly used in drives for heavy-duty traction, power quality management, and magnetic energy storage systems. Based on the integration of the gate turn-off thyristor (GTO) and power MOSFET technology, the emitter turn-off (ETO) thyristor is a new type of superior high-power semiconductor device that is suitable for use in high-frequency and high-power converters [1-5]. By optimally integrating commercial GTOs with MOSFETs, the ETO offers the advantages of fast switching speed, snubberless turn-off capability and voltage control. These merits enable the ETO the ability to achieve high power and high switching frequency. Although the ETO's snubberless turn-off performance has been analyzed in detail [1-5], the ETO's turn-on performance, which is also very important for high-frequency switching, has never before been analyzed and experimentally demonstrated. In this paper, the uniform turn-on process of the ETO is analyzed and experimentally characterized for the first time.

II. THE TURN-ON PROCESS OF THE ETO

An ETO is formed by using a GTO in series with an emitter switch Q_E. The gate switch Q_G is also connected to the GTO's gate, as shown in Fig. 1 [1-3]. During a normal forced turn-off transient, Q_E is turned off and Q_G is turned on. The turn-off of the emitter switch Q_E cuts off the GTO's cathode current path, and all of the cathode currents are quickly transferred to the gate path. In this way, the latch-up mechanism of the GTO is broken and the ETO is turned off under a unity-gain turn-off condition (also known as a hard-driven turn-off condition). Therefore, the ETO has a wide reverse biased safe operation area (RBSOA) and snuberless turn-off capability. Fig. 2 shows a 4-kA/4.5-kV ETO developed at Virginia Tech by the authors in [4-5].

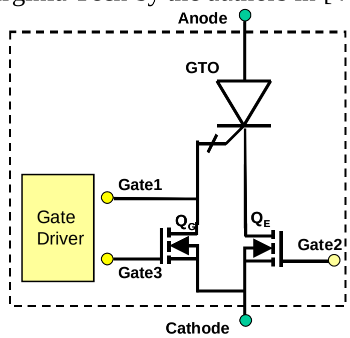


Fig. 1. Equivalent circuit of the ETO.

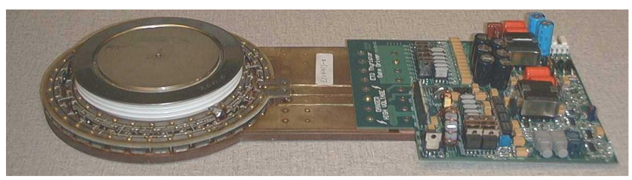


Fig. 2. Picture of the developed 4-kA/4.5-kV ETO with the integrated gate driver.

During the turn-on transient, Q_E is turned on and Q_G is turned off. A high-current pulse is injected into the GTO gate to reduce the turn-on delay time and improve the turn-on di/dt rating. The built-in PNP and NPN transistors inside the GTO latch up quickly, and the anode voltage of the ETO collapses to a low voltage. So the turn-on process of the ETO is similar to that of a GTO [6-8]. Depending on the amplitude and rise rate of the gate current as well as the structure of the GTO, an ETO can be uniformly or non-uniformly turned on. Since the gate driver of the ETO is tightly integrated with the ETO, the ability to provide the desired gate turn-on current is greatly improved compared with that of the GTO.

A. The non-uniform turn-on process

The schematic structure of an ETO is shown in Fig. 3. Generally, the non-uniform turn-on transient process of the ETO is almost the same as that of a GTO, and can be divided into three intervals [6-7]: the delay time t_d, the voltage fall time t_f, and the current rise time t_r, as indicated in Fig. 4 (a). The non-uniform turn-on process will proceed if the gate current amplitude (I_{Gm}) and the rate of increase (dI_G/dt) are below some critical values.

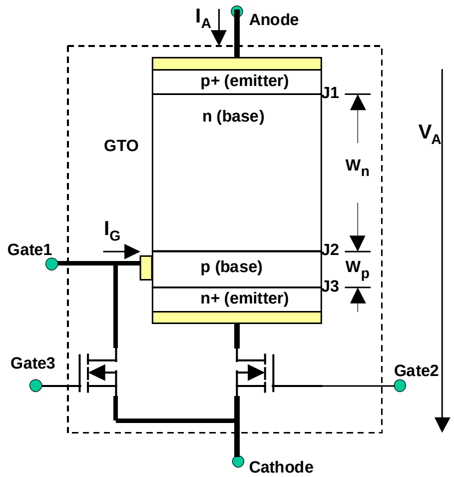


Fig. 3. Schematic structure of the ETO.

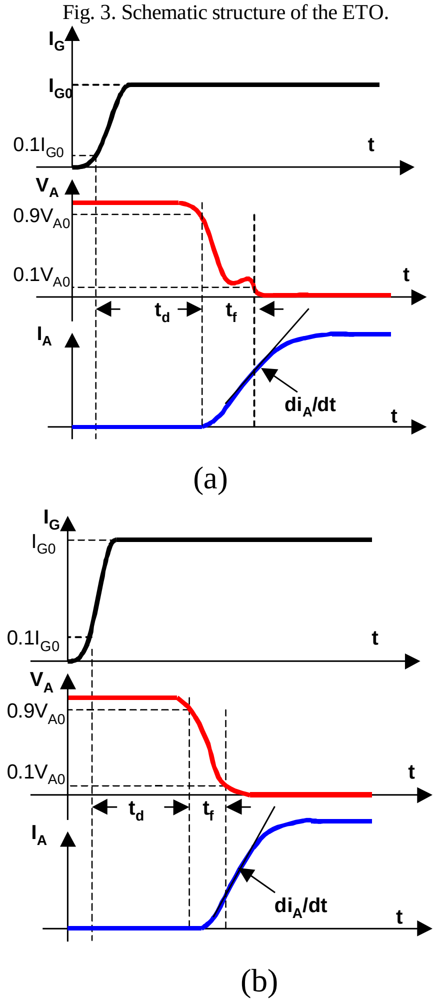


Fig. 4. (a) The ETO's n non-uniform turn-on process and (b) uniform turn-on process.

By applying a pulse current to the gate, the p-base and n+-emitter junction J_3 is forward-biased; excess electrons are then injected from the n+-emitter layer to the p-base layer and then diffuse towards the base-collector junction J_2. At the same time, excess holes are provided by the gate current I_G in order to maintain space charge neutrality. Therefore, the conductivity of the p-base is heavily modulated. The diffusing electrons that do not recombine in the p-base will reach the edge of the J_2 space charge region after the delay time t_p, which is given by

$$t_p = W_{p(undep.)}{}^2 / 2D_n \ , \qquad (1\text{-}1)$$

where $W_{p(undep.)}$ is the width of the un-depleted p-base and D_n is the electron diffusion coefficient.

Having reached the J_2 space charge region, the electrons are quickly swept through by the built-in electric field. When approaching the junction J_1, these electrons will serve as excess majority carriers and will lower the potential of the n-base layer. So the forward bias across junction J_1 is increased and holes are injected from the p+-emitter into the n-base layer. Some injected holes are recombined in the n-base, while others will diffuse through the un-depleted n-base towards junction J_2. These holes will reach the edge of the J_2 space charge layer after a transient time interval t_n, which is given by

$$t_n = W_{n(undep.)}{}^2 / 2D_p \ , \qquad (1\text{-}2)$$

where $W_{n(undep.)}$ is the width of the un-depleted n-base and D_p is the hole diffusion coefficient. The holes are then instantaneously swept across junction J_2 and into the p-base region. These injected holes serve as excess majority carriers and will cause the increased injection of electrons from the n+-emitter into the p-base. As a result, positive feedback is formed.

The delay time t_d is defined as the transient time between the moment the gate current increases to 10% of the final value and the time when the anode voltage decreases to 90% of the initial value, as indicated in Fig. 4. It is the time from the application of the gate current to the moment the J_2 space charge region starts to be discharged. In the case of the GTO, the rate at which the gate current is applied is generally low, and the delay time t_d is generally larger than the transient time for the carriers diffusing through the base region. So,

$$t_d \geq t_n + t_p = W_{p(undep.)}{}^2 / 2D_n + W_{n(undep.)}{}^2 / 2D_p \ . \qquad (1\text{-}3)$$

In the next phase, during the voltage fall time, the J_2 space charge region is quickly flooded with excess carriers. The positive space charge region in the n-base is discharged by the electrons injected from the n+-emitter over junction J_3, and the negative space charge region in the p-base is discharged by the holes injected from the p+-emitter over J_1. So the thickness of the J_2 space charge region is reduced, resulting in both the fall of the anode voltage and the increase of the anode current. The voltage fall time t_f is defined as the time it takes for the anode voltage to be reduced from 90% to 10% of its initial value, as indicated in Fig. 4.

With the formation of positive feedback, after the anode current exceeds the latching current, the gate has little control over the turn-on process. The rise of the anode current is dictated by the physical process of the device as well as the constraints of the external circuit. Since the slowly applied gate current initially only turns on a small area of the GTO, the turn-on process begins with a small cathode area close to gate contact and spreads to adjacent regions. The typical spreading speed is about 5000 cm/s [9]. To avoid the localized overheating effect and to prevent turn-on failure in the device, an external inductor is usually used in the external circuit to limit the anode current rise rate to a level below the critical di_A/dt. The critical di_A/dt for the commercial GTO devices is usually below 1000 A/μs. To ensure that the entire junction area is uniformly turned on before turn-off switching, a minimum turn-on time (usually about 100 μs) is required for commercial GTO devices. The typical non-uniform turn-on waveforms are shown in Fig. 4(a). Another way of describing the non-uniform turn-on is that the turn-on process relies heavily on the self-regenerative process of the thyristor latch-up. Carriers needed for conductivity modulation are provided from the anode and cathode sides, not from the gate drive circuit (or they are only partially provided from the gate drive circuit).

B. The uniform turn-on process

Thanks to the ETO's low-inductance (about 10 nH) gate loop, a gate current with larger amplitude and rise rate can be applied during turn-on. Through applying a gate current pulse with higher amplitude, the excess carriers can be accumulated quickly in the p-base and n-base regions during delay time t_p. The excess electrons injected from the n+-emitter will diffuse towards junction J_2 and will discharge the positive space charge region in the n-base once they have passed through J_2. At the same time, holes provided by the gate current will discharge the negative space charge region in p-base. Before the holes injected from the anode p+-emitter can diffuse through the un-depleted n-base and reach the negative space charge region in the p-base, the J_2 space charge region has already been discharged. In other words, the built-in NPN transistor is turned on uniformly within the initial phase, then operates in the active region, quickly moving across its active region towards the quasi-saturation region before the thyristor latch-up action begins, at which point the anode current increases significantly. Another way to look at this is that the NPN transistor is turned on quickly into the saturation region before the PNP transistor starts to turn on. In this type of turn-on, the charges required to maintain the NPN transistor within the saturation region are provided by the gate drive unit. Little charges are injected from the anode side. In this case, the turn-on delay time t_d is larger than t_p and is less than t_p+t_n.

To achieve this type of turn-on, during the delay time t_d, the gate current should deliver enough charge to discharge the J_2 space charge region. So the gate current required to uniformly turn on the ETO is given as

$$I_G t_d > Q_{GT} \ , \qquad (1\text{-}4)$$

where Q_{GT} is the charge needed to turn on the GTO device and discharge the space charge region. Therefore,

$$Q_{GT} \geq A \cdot W \cdot n^* \cdot q / \gamma_n \ , \qquad (1\text{-}5)$$

where γ_n is the J_3 emitter injection efficiency, A is the device area, W is the total n-base and p-base width, and n* is a modulated carrier plasma level, which is much higher than the n-base background doping N_D.

So, $$I_G > A \cdot W \cdot n^* \cdot q / \gamma_n / t_d \ . \qquad (1\text{-}6)$$

It can be seen from Equation 1-6 that a larger ETO device requires a higher gate current in order to achieve uniform turn-on. The gate current rise rate (dI_G/dt) should satisfy the following:

$$\frac{dI_G}{dt} >> \frac{I_G}{t_d} \ . \qquad (1\text{-}7).$$

During the voltage fall phase, the anode voltage collapses quickly, while the anode current stays at a low level, as shown in Fig. 4 (b). The anode voltage continues to drop until reaching a saturation voltage level in spite of the increase in anode current. The turn-on loss is therefore reduced since there is not much overlap between the anode voltage and current. Under this condition, the GTO is uniformly turned on without current-crowding problems. Therefore, the critical anode current rise rate can be increased. The minimum on-time can also be reduced since the turn-on process of the GTO in this case is more similar to that of a transistor than it is to a thyristor. Under this condition, the ETO's turn-on performance is greatly improved.

It should be mentioned that at a higher anode current rise rate (which is limited by the external di/dt inductor), an anode voltage bump may occur, indicating either that there is still an unmodulated n-base region, or that the n* level provided by the gate current is still too low. To eliminate this bump, a gate current with an even higher amplitude is required to increase n* in Equation 1-6. In other words, one indication of uniform turn-on (this is of course a relative term depending on what dI_A/dt is applied) is that the voltage fall phase has no bump during the high-current rise phase.

III. ETO Gate Drive Circuit

The ETO's gate drive circuit and control signals are shown in Fig. 5. Following the turn-on command, switch Q_P is turned on and the 18-V voltage source begins to charge the inductor L_p through Q_p, L_p and Q_G. After a charging time t_P, Q_P is turned off and the current in L_p freewheels through Q_G and D_P. Then, Q_G is turned off and Q_E is turned on. The current in Q_G will be transferred instantaneously to the GTO's gate, since the inductor L_p serves as a current source at this moment. The current decrease rate in Q_G, which is also the gate current rise rate, is dictated only by the breakdown voltage of Q_G (about 55 V) and the gate loop inductance (about 10 nH). Thus, the gate current rise rate can be as high as 5 kA/µs, which is high enough to uniformly turn on the ETO. Once the current in L_p is totally commutated to GTO's gate, it will freewheel through emitter switch Q_E and diode D_p and then slowly drop down to zero, as shown in Fig. 5(b). By varying the charging time t_P, gate current pulses with different amplitudes can be obtained and the ETO's corresponding turn-on performance can be characterized.

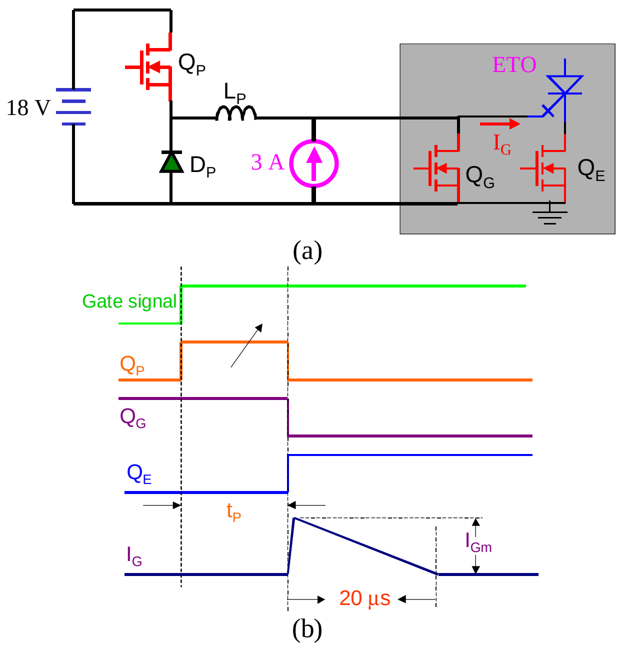


Fig. 5. (a) The ETO's gate drive circuit and (b) control signals.

IV. Experimental And Simulation Results

By varying the amplitude of the gate current, the ETO's turn-on performances at different current levels are tested. Fig. 6 (a) shows the turn-on waveforms of the 1-kA/4.5-kV ETO1045SW under a gate current pulse with 200-A amplitude and anode current rise rate of 500 A/µs. Once the gate current pulse is applied to the GTO's gate, the anode voltage begins to drop within 100 ns. Such a short t_d is another indication of a good turn-on. Then, the anode voltage quickly collapses from 2 kV down to 200 V within 100 ns, in spite of the increase in anode current. Since the anode current is still low at this point, the built-in NPN transistor is turned on into the quasi-saturation region before the thyristor latches up. In this case, the ETO behaves like a transistor instead if a thyristor. So the ETO is uniformly turned on. The turn-on loss is reduced and the critical di/dt of the anode current can be increased.

When the gate current amplitude is reduced to 150 A, the anode voltage collapses quickly at the beginning but a small shoulder around 350 V presents, as shown in Fig. 6(b). In this case, the reduced gate current and the corresponding injected electrons from the n+-emitter cannot completely discharge the J_2 space charge region before the PNP starts to inject and before the thyristor latches up. A small space charge region is maintained until it is discharged by the increased anode current. As a result, the thyristor latch-up action does not occur simultaneously in all cells. In a manner similar to that of the traditional GTO, the ETO is non-uniformly turned on and the turn-on loss is increased.

If the gate current amplitude is further reduced to 100 A, the anode voltage has an even higher voltage bump that presents for a longer time, as shown in Fig. 6(b). Therefore, to achieve the uniform turn-on of the 1-kA/4.5-kV ETO1045SW (under the 500-A/µs anode current rise rate condition), a gate current pulse with 200-A amplitude is required.

Calculation using Equation 1-6 for the ETO1045SW will result in a gate current of about 202 A using $n^*=10^{14}$ cm^{-3}, t_d = 0.1µs, γ_n = 0.6, A = 15.9 cm^2, and W = 500 µm.

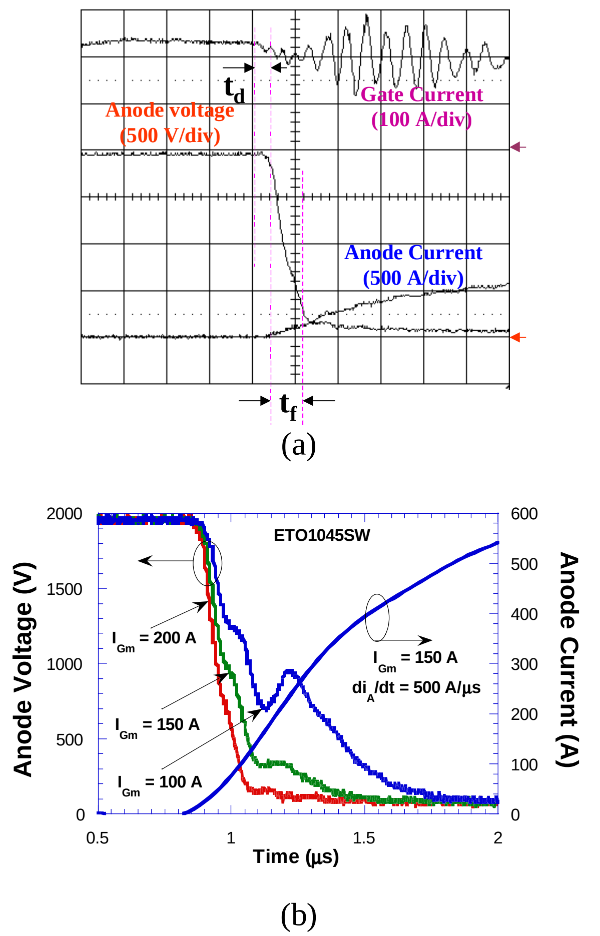


Fig. 6. (a) Turn-on waveforms (I_{Gm} =200 A, Time: 200 ns/div) and (b) turn-on waveforms comparison of the 1-kA/4.5-kV ETO1045SW (di_A/dt = 500 A/µs).

To better understand the uniform turn-on mechanism of the ETO, the turn-on process of a 1-kA/4.5-kV ETO was analyzed with the help of mixed-mode 2-D simulations [10]. With the same gate drive circuit and turn-on test setup as those used in the experiments, the resulting simulated turn-on waveforms are displayed in Fig. 7. Similar to the experimental results, when the gate current amplitude is 300 A and the anode current rise rate is 500 A/µs, the ETO's voltage collapses quickly from 2 kV to about 200 V within 200 ns and continues to decrease to the saturation voltage level, as shown in Fig. 7. In this case, the ETO is uniformly turned on without current-crowding problems. When the gate current amplitude is reduced to 150 A, the anode voltage drops quickly at the beginning, and a small voltage bump is presented around 1200 V due to the increased anode current. In this case, the ETO is non-uniformly turned-on. The voltage decrease time is longer and the anode current increase rate is limited to avoid current filamentation failure.

To get more insight into the uniform turn-on process, the carrier distributions at the center of the GTO cell during the turn-on transient (under 300-A gate current amplitude condition) are displayed in Fig. 8, with the cathode located at 0.00 µm. As shown in Fig. 8(a), the electrons flood the space charge region within 100 ns. However, the holes are delayed by about 200 ns from filling the space charge region, as shown in Fig. 8(b). Thus, with the high gate current amplitude (above 200 A) and huge gate current rise rate (about 5 kA/µs), the thyristor latch-up action is delayed about 200 ns and the transistor-like uniform turn-on of the ETO is achieved.

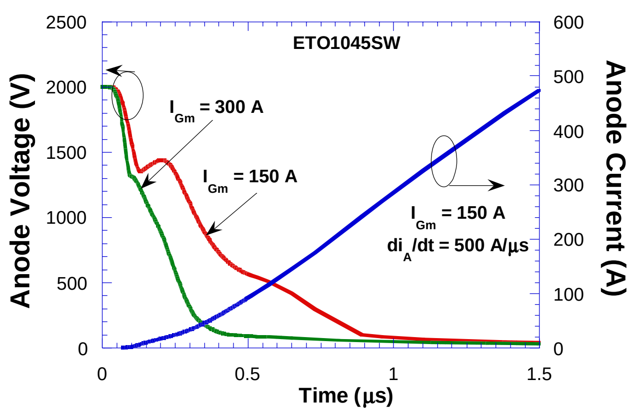
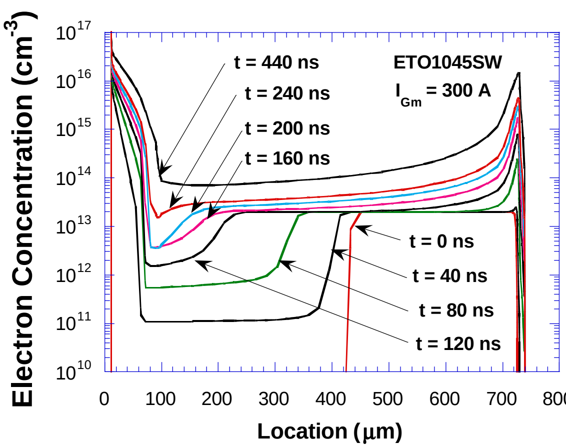
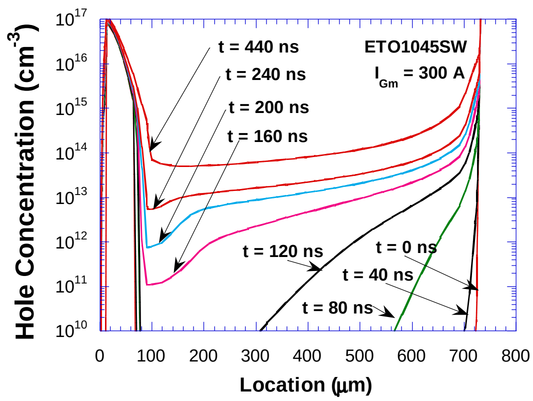


Fig. 7. Simulated turn-on waveforms of the 1-kA/4.5-kV ETO1045SW.



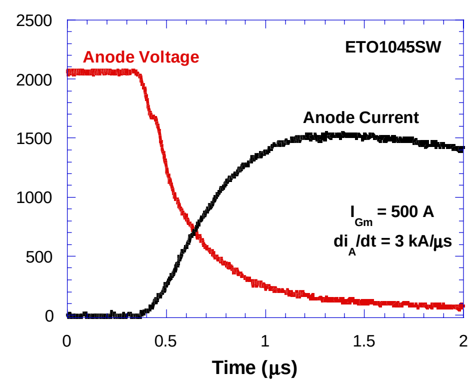
(a)



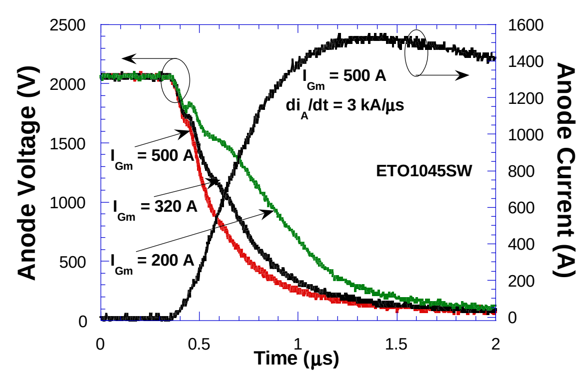
(b)

Fig. 8. The center of the cell of the 1-kA/4.5-kV ETO1045SW during the uniform turn-on transient (di_A/dt = 500 A/µs): (a) electron concentration and (b) hole concentration.

As mentioned before, with a higher anode current rise rate, a gate current with higher amplitude is needed in order to compensate for the fast climbing speed of the anode voltage. When the anode current rise rate is 3 kA/µs, a gate current with 500-A amplitude is needed to uniformly turn on the 1-kA/4.5-kV ETO1045SW, as shown in Fig. 9. The minimum on-time is reduced to less than 20 µs, as shown in Fig. 10.



(a)



(b)

Fig. 9. The 1-kA/4.5-kV ETO1045SW (di_A/dt = 3000 A/µs): (a) turn-on waveforms (I_{Gm} =500 A) and (b) turn-on waveforms comparison.

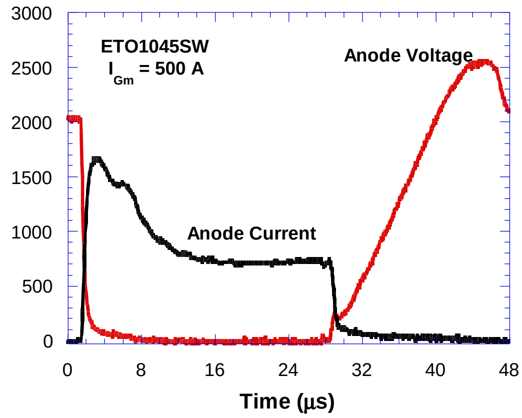
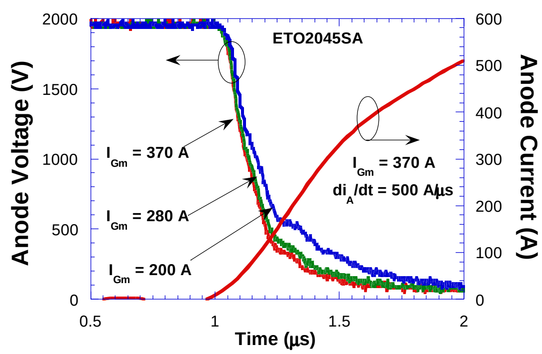
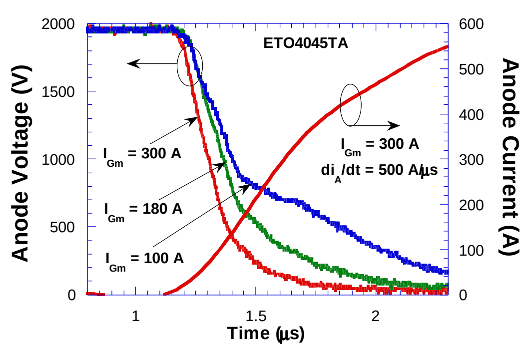


Fig. 10. Turn-on and turn-off waveforms (I_{Gm} =500 A) of the ETO1045SW (di_A/dt = 3000 A/µs).

According to Equation 1-6, for a larger-area device, a gate current with higher amplitude is required to achieve uniform turn-on. Fig. 11 displays the turn-on waveforms for the 2-kA/4.5-kV ETO2045SA and the 4-kA/4.5-kV ETO4045TA. To achieve uniform turn-on (under the 500-A/µs anode current rise rate condition), the gate current pulses with 280-A and 300-A amplitudes are required.



(a)



(b)

Fig. 11. Turn-on waveforms comparison for (a) 2-kA/4.5-kV ETO2045SA and (b) 4-kA/4.5-kV ETO4045TA.

V. Conclusion

Through theoretical analysis and experiments, the ETO's turn-on performance is characterized for the first time. Due to the low gate loop inductance, a gate current pulse with high amplitude and huge rise rate (about 5kA/µs) can be applied. Therefore, the ETO can be uniformly turned on without current-crowding problems. Correspondingly, the critical anode current rise rate is improved and the minimum turn-on time is reduced. These advantages, together with the snubberless turn-off capability and voltage control, make the ETO a very promising device for high-power high-frequency power electronics systems.

Acknowledgments

This work was supported by the Tennessee Valley Authority (TVA) and the US Department of Energy under a grant managed by the Sandia National Labrotory. This work also made use of ERC shared facilities supported by the National Science Foundation under Award Number EEC-9731677.

References

[1] Y. Li, A. Q. Huang and F. C. Lee, "Introducing the emitter turn-off thyristor (ETO)," IEEE Industry Applications Society 33st Annual Meeting, Oct. 12-15, 1998, pp. 860-864.

[2] A. Q. Huang, Y. Li, K. Motto, A. Z. Xu and F. C. Lee, "High power snubberless switching with the emitter turn-off thyristor (ETO)," PCIM'98 Power Electronics Conference, Santa Clara, California, Nov. 7-13, 1998, pp. 269-279.

[3] Zhenxue Xu, Yuxin Li and Alex Q. Huang, "Performance characterization of 1-kA/4.5-kV symmetrical emitter turn-off thyristor (ETO)," IEEE IAS 2000, Oct. 2000, pp. 2880-2884.

[4] Kevin Motto, Yuxin Li, Zhenxue Xu and Alex Q. Huang, "High frequency operation of a megawatt voltage source inverter equipped with ETOs," IEEE APEC 2001, March, 2001, pp. 924-930.

[5] Zhenxue Xu, Kevin Motto and Alex Q. Huang, "Abnormal failure mechanism of the asymmetrical emitter turn-off thyristor in high-frequency converters," IEEE IAS 2001, Oct. 2001, pp. 1504-1509.

[6] H. E. Gruening and A. Zuckerberger, "Hard drive of high power GTOs: better switching capability obtained through improved gate-units," IEEE IAS 1996, Oct. 1996, pp. 1474-1480.

[7] V. Benda, John Gowar and Duncan A. Grant, "Power semiconductor devices," John Wiley and Sons, Inc., 1999, pp. 186-230.

[8] O. H. Stielau, J. J. Schoeman and J. D. Van Wyk, "A high-performance gate/base drive using a current source," IEEE transactions on Industry Applications, Sep./Oct. 1993, pp. 933-939.

[9] B. Jayant Baliga, "Power semiconductor devices," PWS Publishing Company, 1996, pp. 272-295.

[10] MEDICI User Manual, Technology Modeling Associates, Inc., 1998.