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ULTRA HIGH di/dt PULSE SWITCHING OF 2500 V MOS ASSISTED GATE-TRIGGERED THYRISTORS (MAGTs)

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ABSTRACT

An ultra high di/dt 2500 V MOS Assisted Gate-triggered Thyristor (MAGT) was developed to replace a thyratron in pulsed power applications, such as high repetition (>1 kpps) excimer lasers. The main objective in developing such devices is to realize extremely low transient turn-on power losses, while still retaining high breakdown voltages. The MAGT exhibits the much higher turn-on characteristics than that for IGBTs. It is shown that 40 kA/μs/cm^2 for di/dt can be attained for a turn-on from 1500 V anode voltage, 9090 A/cm^2 peak anode current, and 0.7 μs pulse width, with an extremely low turn-on power loss.

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INTRODUCTION

Much progress has been made in achieving functionally integrated MOS-bipolar devices, in regard to their maximum controllable power. Especially, IGBTs have attained a high forward blocking voltage (~1800 V) (1), and a large current handling capability (~400 A) (2). Now, they are widely used for many applications, such as replacing conventional bipolar transistors, to take advantage of their easy driving and fast switching capabilities. However, higher forward blocking voltages (>2000 V) lead to unacceptable high on-state voltages, even in IGBTs. Therefore, a new class of integrated MOS-bipolar devices, based on the thyristor mode operation, has been actively studied (3)-(8).

Their application range has now been extended to new fields, including pulsed power applications, such as high repetition excimer lasers (>1 kpps) (9). Although thyratrons are commonly used to generate very short high current pulses for this

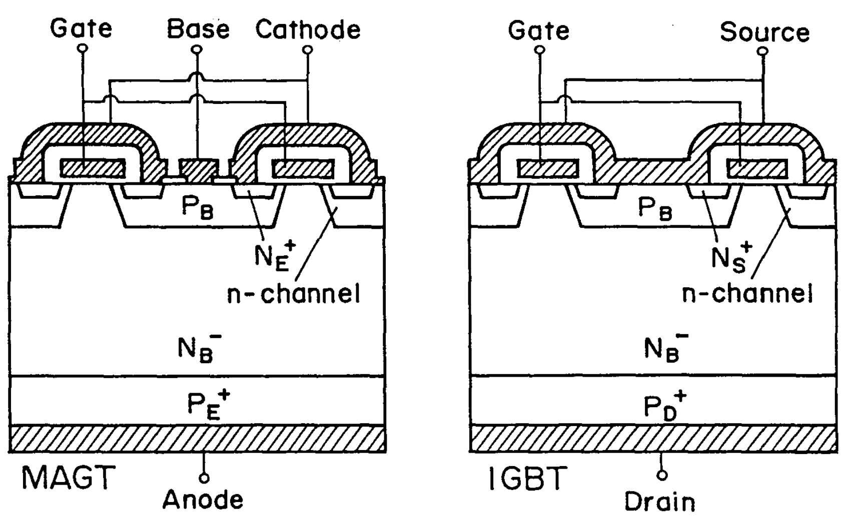


Fig.1 Basic structures for MAGT (left) and IGBT (right).

field, their lifetime (10^8 shots) and reliability are not adequate for use in high repetition excimer lasers. Although many efforts to replace thyratrons with conventional high power semiconductor devices have been made recently (10)-(12), their large turn-on power losses prevent them from being applied to high repetition excimer lasers. The investigation on IGBT switches applied for this objective started recently (9). However, its application area is limited to small power lasers, because of their current saturation characteristics. Therefore, power semiconductor devices, which can switch pulsive high current at high repetition rate, are urgently required. This paper proposes an MOS Assisted Gate-triggered Thyristor (MAGT) for pulsed power applications. It is shown that the transient turn-on power loss can be extremely reduced, even in the high di/dt ratio.

DEVICE STRUCTURE

The MAGT basic device structure is shown in Fig.1, compared with the IGBT device structure. The MOS gate electrode is placed on the edge of the p-base layer (P_B) to turn-on this thyristor with a high di/dt ratio. A base electrode is placed on the p-base layer (P_B), to ensure constant p-base potential and high dv/dt immunity, while the source electrode contacts both the source layer (N_S^+) and the p-base layer(P_B) in the IGBT structure.

The n-base width is minimized, contingent upon the forward blocking voltage being maintained, in order to rapidly increase the n-base carrier density. The impurity profile is designed to attain high trigger sensitivity. The gate electrode length and the n-emitter length are optimized, considering on-state voltages and di/dt characteristics.

When a positive bias is applied to the gate electrode, electrons are directly injected from the cathode electrode toward the n-base layer (N_B) through the n-channel, resulting in a rapid increase in the n-base electron density. This rapid electron injection urges hole injection from the anode electrode. Then, electrons are injected from the emitter junction, and the MAGT is latched up within some tens of nano seconds. This is because the p-base potential is fixed by the base electrode, instead of the emitter short, to rise the emitter injection efficiency.

When the MAGT must be in its off-state, a negative bias is applied to the base electrode. The leakage current in the off-state, and the displacement current caused by a high dv/dt are extracted from the base electrode. It prevents the sensitive MAGT from being mis-triggered.

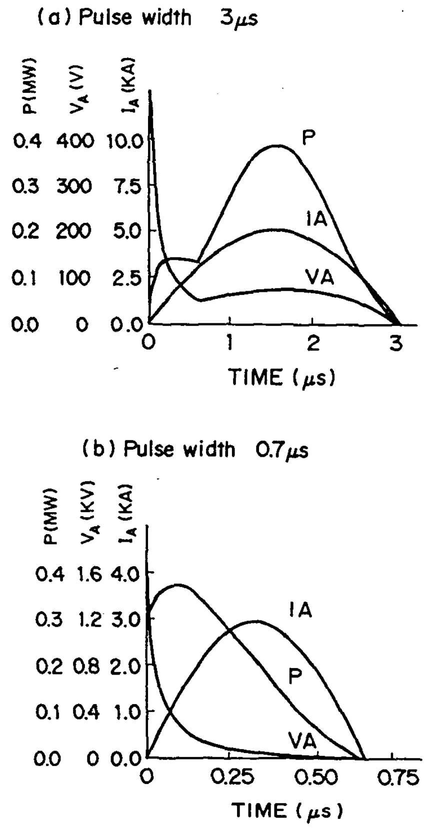


Fig.2 Calculated turn-on waveforms for anode current (I_A), anode voltage (V_A) and power loss (P).

CALCULATION

Numerical calculations were carried out to estimate the turn-on power loss for an approximate model, while making the following simple assumptions.

1) The n-base resistance is in inverse proportion to the average n-base carrier density.
2) Carrier recombination is negligible, and the whole anode current contributes to the carrier accumulation in the n-base.
3) The average n-base carrier density does not exceed 1×10^{17} cm^{-3}.
4) The whole device area turns on uniformly, by adopting a VLSI fine process technology.

Figure 2 shows the calculated turn-on waveforms for an ideal condition in the two different excimer laser power unit circuits.

Figure 2 (a) indicates that turn-on power loss consists of two peaks, when pulse width is 3 μs. One is the small peak caused by high di/dt. The other is the large peak caused by the following high anode current. On the contrary, turn-on power loss is caused by only high di/dt, when pulse width is 0.7 μs, as shown in Fig.2 (b). Consequently, it is understood that the on-state voltage is the primary concern for the 3 μs pulse width case, while the rapid turn-on has to be attained for the 0.7 μs pulse width case. In other words, conventional slow discrete power devices are suitable for the 3 μs pulse width case, while high di/dt triggered power devices, like MAGTs, are suitable for the 0.7 μs pulse width case. From the laser application point of view, the shorter pulse width is desirable, because the higher circuit efficiency is attained by the reduction in additional magnetic pulse compression circuit.

FABRICATION

Small sized devices (3.3 mm × 4.9 mm chips) were fabricated in order to demonstrate the high di/dt, high power pulse switching for MAGTs. Figure 3 shows the fabricated device mounted onto a stem.

The process steps are similar to those for a conventional IGBT. The starting material is a high resistivity neutron doped FZ-Si wafer, whose resistivity and thickness are determined for the requested forward blocking voltage. The base electrode was separated from the cathode electrode, to form the MAGT device structure. IGBT pellets were fabricated under identical processes for comparison. Some of these chips were subjected to a lifetime reduction by electron beam irradiation, in order to gain a high dv/dt immunity.

RESULTS

Forward blocking voltage

A 2500 V forward blocking voltage was realized by a resistive field plate junction termination structure (1),(13), as is shown in Fig.4.

On-state voltage

Figure 5 shows the V-I characteristics for a fabricated MAGT and IGBT. The MAGT can handle 10 kA/cm² at 7 V for the on-state voltage, taking advantage of the thyristor mode operation, while the IGBT is saturated at 300 A/cm². Therefore, the IGBT application area is limited to small power lasers, because the peak of pulsive current must be smaller than the saturation current. High power handling capability is an indispensable feature for pulsed power switches.

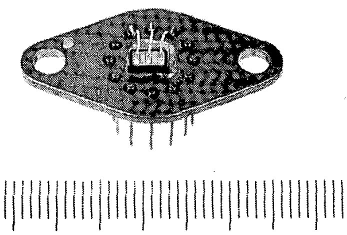


Fig.3 Fabricated MAGT pellet.

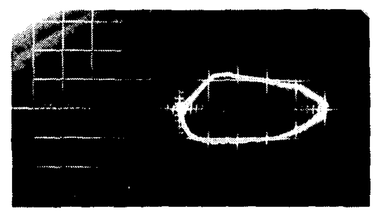


Fig.4 Fabricated MAGT forward blocking voltage. (V_A:500 V/div., I_A:100 μA/div.)

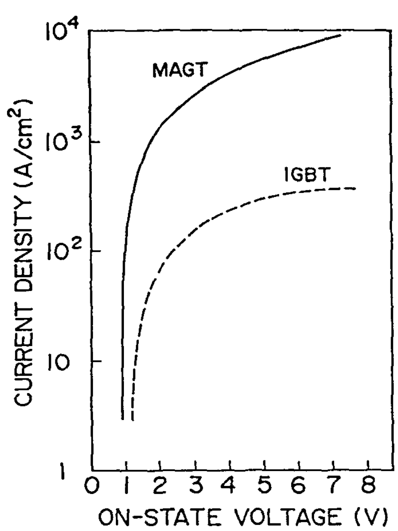


Fig.5 V-I characteristics for fabricated MAGT and IGBT.

Turn-on characteristics

Figure 6 shows the test circuit for measuring turn-on waveforms. The appropriate values for capacitance (C) and inductance (L) were selected for each condition in the peak anode current and the anode current rising rate di/dt.

Figure 7 shows the turn-on waveform for an IGBT. A steep increase in the drain voltage was observed corresponding to the peak drain current (I_{DP}), because of the drain current saturation.

The turn-on waveforms for 0.1, 0.7, and 3 μs pulse widths are shown in Fig.8. It is apparent that the transient anode voltage is significantly reduced for an MAGT. No steep increase in the anode current is observed. Little anode voltage increase is observed, for 3 μs pulse width case. For 0.7 μs pulse width case, the transient anode voltage, caused by high di/dt, is less than 100 V, even in the case of 9090 A/cm² for the peak anode current density (I_{AP}), and up to 40 kA/μs/cm² of di/dt can be obtained. No anode voltage peak is observed at the peak anode current, which agrees with the calculation result for the approximate model. It is also shown that the turn-on power loss is higher than that for the other cases, because the anode voltage decreases during the steep increase of the anode current, for the 0.1 μs pulse width case.

Figure 9 shows turn-on power loss dependence on the pulse width for a 5 kpps operation, when the product of the peak anode current (I_{AP}) and the pulse width (tw) is constant, which corresponds to the pulse width adjustment in the actual laser power supply. In this figure, the 1st part is the power loss generated during the rising time. The 2nd part is the residual part of the total power loss. The 1st part monotonically decreases as the pulse width increases, which corresponds to the di/dt decrease. On the contrary, the 2nd part increases below 0.4 μs pulse width, and slowly decreases after that. Therefore, the total power loss is not so high, when more than 0.5 μs pulse width is chosen. It is also understood that a threefold large device area is needed for the 0.1 μs pulse width operation, which corresponds to the direct drive for a laser head without any additional magnetic pulse compression circuit.

Figure 10 shows turn-on power loss dependence on I_{AP}*tw for a 5 kpps operation. As mentioned before, the turn-on power loss for the 0.7 μs pulse width case is slightly larger than that for the 3 μs pulse width case. Therefore, the turn-on power loss value can be determined for the requested laser power, when more than 0.5 μs pulse width is used. The designed device area depends on the thermal resistance for the package, and the requested I_{AP}*tw.

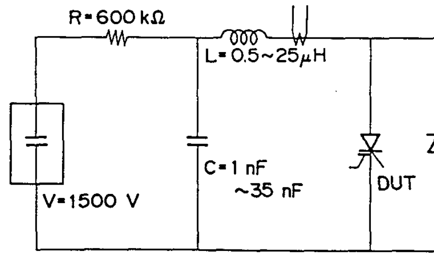
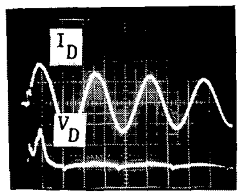
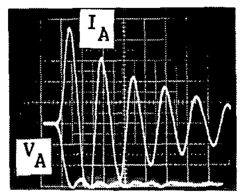


Fig.6 Test circuit for measuring the di/dt behavior.



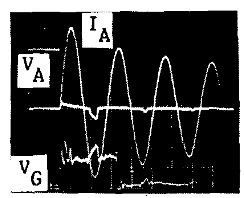
I_{DP}=19 A (400 A/cm²)
I_D:10 A/div.
V_D:200 V/div.
t :0.5 μs/div.
Pulse width 0.7 μs

Fig.7 Turn-on waveform for drain current (I_D) and drain voltage (V_D) for the IGBT.



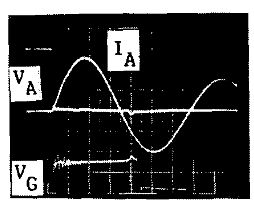
I_{AP}=45 A (2.0 kA/cm²)
dI_A/dt=1.2 kA/μs
(55 kA/μs/cm²)
I_A:10 A/div.
V_A:500 V/div.
t :0.1 μs/div.

(a)Pulse width 0.1 μs



I_{AP}=200 A (9.1 kA/cm²)
dI_A/dt=0.86 kA/μs
(40 kA/μs/cm²)
I_A:50 A/div.
V_A:500 V/div.
V_G:20 V/div.
t :1 μs/div.

(b)Pulse width 0.7 μs



I_{AP}=125 A (5.7 kA/cm²)
dI_A/dt=0.13 kA/μs
(5.7 kA/μs/cm²)
I_A:50 A/div.
V_A:500 V/div.
V_G:20 V/div.
t :1 μs/div.

(c)Pulse width 3 μs

Fig.8 Turn-on waveforms for anode current (I_A), anode voltage (V_A), gate voltage (V_G) for a fabricated 2500 V MAGT.

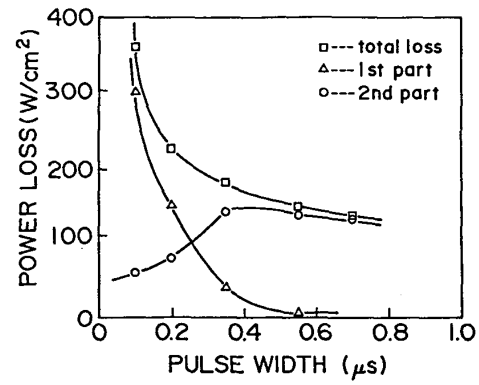


Fig.9 Turn-on power loss dependence on pulse width.

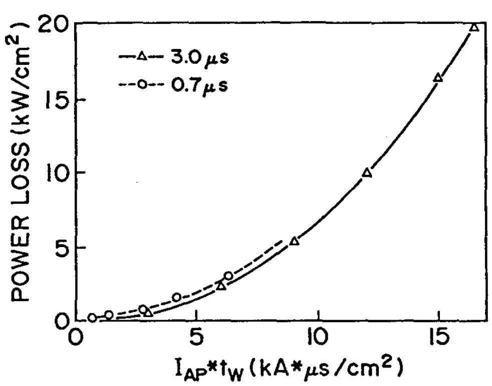


Fig.10 Turn-on power loss dependence on I_{AP}*tw.

dv/dt immunity

The MAGT shows excellent dv/dt immunity, when a negative bias is applied to the base electrode. However, the displacement current, flowing from the base electrode, leads to a large power dissipation, when high dv/dt is applied soon after a large pulsive current. Therefore, lifetime reduction by electron beam irradiation was examined.

Figures 11 and 12 show the V-I characteristics and the turn-on power loss dependence on peak anode current, respectively, for the 0.7 μs pulse width case. Although the on-state voltage for MAGT with electron beam irradiation was higher than that for the other, as shown in Fig.11, the turn-on power loss difference between them is very small, as shown in Fig.12. This is because the turn-on power loss is mainly determined by the initial

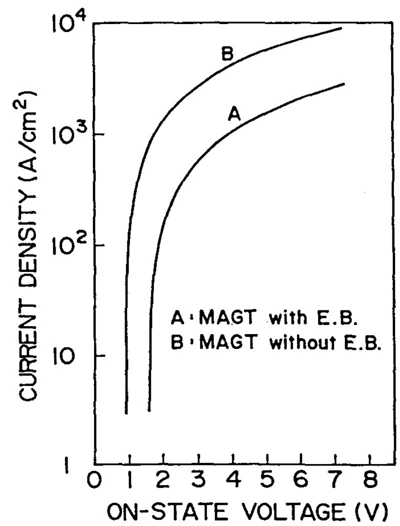


Fig.11 V-I characteristics for fabricated MAGTs (A) with and (B) without electron beam irradiation.

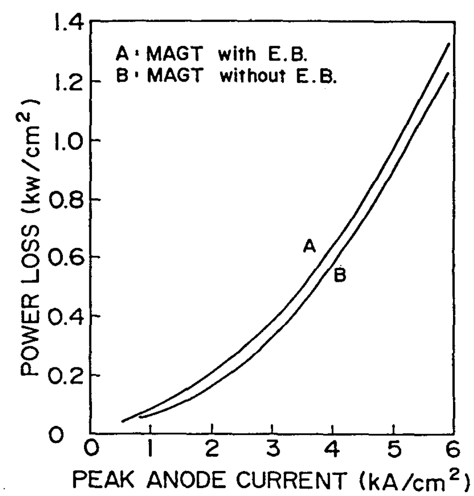


Fig.12 Turn-on power loss dependence on peak anode current for MAGTs (A) with and (B) without electron beam irradiation.

di/dt, and the peak anode current does not exceed the saturation current for MAGTs in the range of this figure.

The extracted base current was much reduced for the MAGT with electron beam irradiation, even when 1000 V/μs of dv/dt was applied.

CONCLUSION

An MOS Assisted Gate-triggered Thyristor (MAGT) was developed, incorporating a power thyristor with the MOS gate electrode, as well as a base electrode. This device showed extremely high di/dt characteristics, while retaining high breakdown voltage (2500 V). The transient anode voltage, caused by high di/dt, is less than 100 V, even in the case of 9090 A/cm² for the anode current density, in the 0.7 μs pulse width case. Therefore, MAGTs are very promising for application to a high repetition excimer laser system.

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