ULTRA HIGH di/dt 2500 V MOS ASSISTED GATE-TRIGGERED THYRISTORS (MAGTs) FOR HIGH REPETITION EXCIMER LASER SYSTEM

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ABSTRACT

High di/dt triggered power semiconductor devices are indispensable for a wide variety of pulsed power applications, such as high repetition excimer lasers (>1 kpps). They realize high reliability systems, replacing thyratrons which have only 10^8 shots lifetime. The main objectives in developing such devices are to realize extremely low transient turn-on power losses, while still retaining high breakdown voltages. This paper proposes a novel MOS Assisted Gate-triggered Thyristor (MAGT) having high di/dt turn-on characteristics. It is shown that 40 kA/cm²/μs of di/dt can be attained for a turn-on from 1500 V anode voltage, 9090 A/cm² 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 functionally integrated MOS-bipolar devices (1)-(15), in regard to their maximum controllable power. Especially, IGBTs have attained a high forward blocking voltage (~1800 V) (5)-(6), and a large current capability (~1000 A) (9). Now, they are widely used for many applications, replacing conventional bipolar transistors, to take advantage of their easy driving and fast switching capabilities. Current main topics concering IGBTs are increasing switching speed with retaining a large SOA (7)-(8). 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 (10)-(15).

Their application range has now been extended to new fields, including pulsed power applications, such as high repetition excimer lasers (>1 kpps) (19). Although thyratrons are commonly used to generate very short high current pulses for this field, their lifetime (10^8 shots) and reliability are not adequate for use in high repetition excimer lasers. Although many efforts on replacing thyratrons with conventional high power semiconductor devices have been made recently (15)-(18), 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 has started recently (19). 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 a 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.

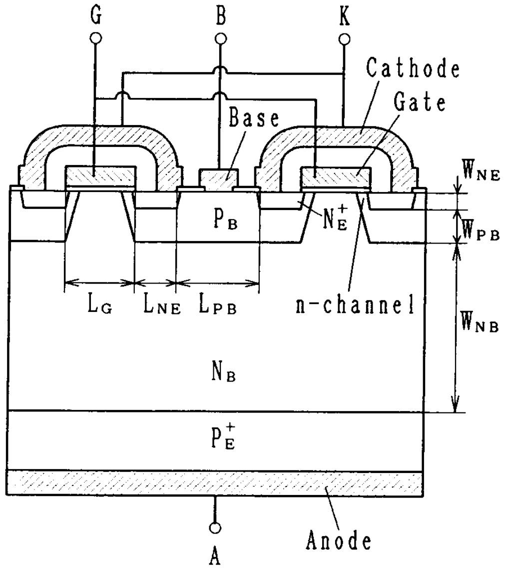

Fig.1 Fabricated MAGT cross-sectional view.

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DEVICE STRUCTURE

The MAGT device structure is shown in Fig.1. A 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. 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), resulting in a rapid increase in the n-base electron density. This rapid electron injection urges hole injection from the anode electrode, and, eventually, the MAGT is turned on. There are some design parameters to be optimized, as shown in Fig.1. Concerning the impurity profiles, the n-base width (W_{NB}), the p-base width (W_{PB}), the n-emitter width (W_{NE}), and concentration for each layer are main parameters. The n-base width must be minimized in order to rapidly increase the n-base carrier density. The p-base width, the n-emitter width, and concentration for each layer must be designed to attain high current gain for the n-p-n transistor, which consists of the n-emitter layer (N_E), p-base layer (P_B), and n-base layer (N_B). Concerning the lateral dimensions, gate electrode length (L_G), n-emitter length (L_{NE}), and p-base length (L_{PB}) are main parameters. An optimum gate electrode length must be determined considering on-state voltages and di/dt characteristics. The n-emitter length must be set so as to turn-on uniformly over the n-emitter area. The p-base length must be minimized by fine pattern processing technique.

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 $1\times10^{17}\mathrm{cm}^{-3}$.
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 0.7μs, as shown in Fig.2(b). Consequently, it is understood that the on-state voltage is the primary concerns for the 3 μs pulse width case, while the rapid turn-on has to be attained for 0.7μs pulse width case.

The turn-on characteristics were evaluated for the 0.7μs pulse width case, because the advantage in the high di/dt capability for this device appears markedly for the 0.7μs pulse width case. Besides, the laser power unit circuit efficiency is higher for this case, than for the 3.0μs pulse width case.

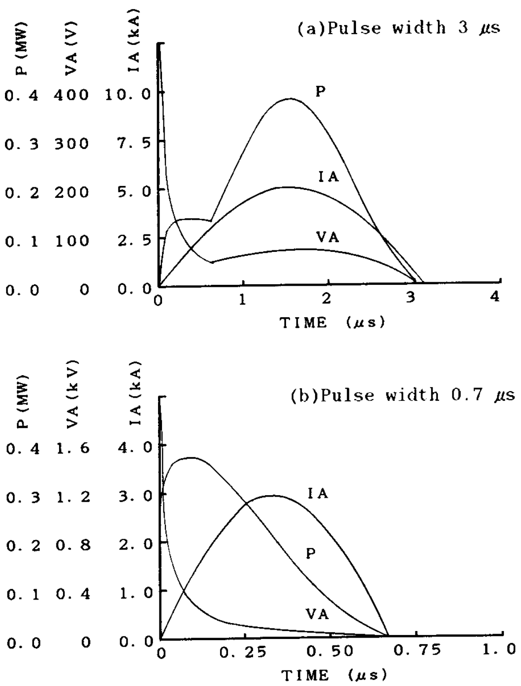

Fig.2 Calculated turn-on waveforms for anode current (I_A), anode voltage (V_A) and power loss (P).

FABRICATION

Small sized devices (3.3mm × 4.9mm chips) were fabricated in order to demonstrate the high di/dt, high power pulse switching of MAGTs. 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 a MAGT device structure. IGBT pellets were fabricated under identical processes for a comparison. Some of these chips were subjected to a lifetime reduction by electron irradiation in order to gain a high dv/dt immunity.

RESULTS

Forward blocking voltage

A forward blocking voltage of 2500 V was realized by a resistive field plate junction termination structure (6),(20) as is shown in Fig.3.

Fig.3 Fabricated MAGT forward blocking voltage. (V_A:500 V/div., I_A:100 μA/div.)

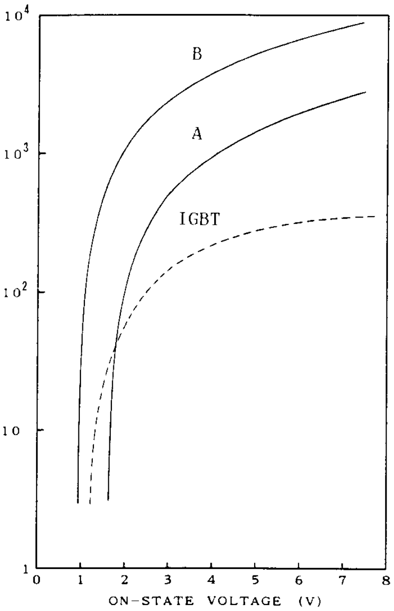

Fig.4 V-I characteristics for fabricated MAGTs (A) with and (B) without electron irradiation (solid line), and IGBT (dashed line).

On-state voltage

Figure 4 shows the V-I characteristics for fabricated MAGTs with and without electron irradiation. The additional curve is that for IGBT. It is apparent that the on-state voltage can be greatly reduced for MAGTs compared with IGBTs. This is because the MAGT n-base is well modulated in conductivity by the thyristor mode operation. Therefore, MAGTs can handle much higher current than IGBTs. This is an indispensable feature for pulsed power switches.

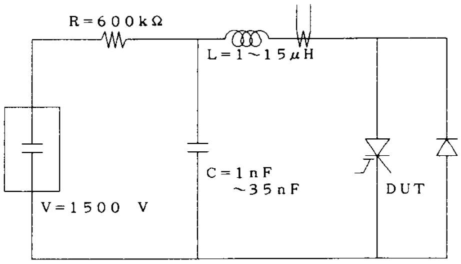

Fig.5 Test circuit for measuring the MAGT di/dt behavior.

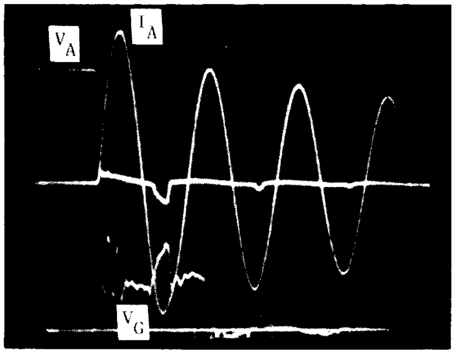

Fig.6 Turn-on waveforms for anode current (I_A), anode voltage (V_A), gate voltage (V_G) for a fabricated 2500 V MAGT.(I_A:50 A/div.,V_A:500 V/div. V_G:20 V/div., t:1 μs/div.)

Turn-on characteristics

Figure 5 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. A typical turn-on waveform for 0.7μs pulse width is shown in Fig.6. The transient anode voltage, caused by high di/dt, is less than 100 V, even in the case of 9090 A/cm^2 for the anode current density, and up to 40kA/cm^2/μs of di/dt can be obtained. No anode voltage peak is observed at the peak anode current, which agrees with the result of calculation for the approximate model. Figure 7 shows turn-on power loss dependence on peak anode current density for a 5 kpps operation. The turn-on power losses for fabricated devices have been reduced to a level of 2~3 times as large as that for the theoretically predicted value. It was also observed that they were not affected by the gate length L_G, when $L_G \geq$ 30 μm. The observed turn-on power loss is 100 W/cm^2 for 600 A/cm^2 peak anode current, 0.7 μs pulse width and 5kpps operation. Therefore, MAGTs are very promising for application to a high repetition excimer laser system.

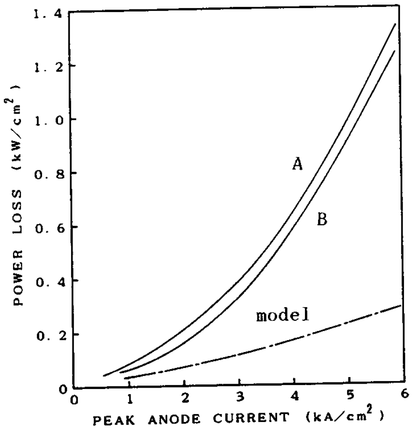

Fig.7 Turn-on power loss dependence on peak anode current for MAGTs (A) with and (B) without electron irradiation (solid line), and the result of the approximate model (dashed line).

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 irradiation was examined. Although the on-state voltage for MAGT with electron irradiation was higher than that for the other as shown in Fig.4, the turn-on power loss difference between them is very small. This is because the turn-on power loss is mainly determined by the initial di/dt. For the MAGT with electron irradiation, little displacement current was observed, when 1000 V/μs of dv/dt was applied.

CONCLUSIONS

A MOS Assisted Gate-triggered Thyristor (MAGT) has been presented, incorporating a power thyristor with the MOS gate electrode, as well as a base electrode. This device shows extremely high di/dt characteristics. The transient anode voltage, caused by high di/dt, is less than 100 V, even in the case of 9090 A/cm^2 for the anode current density, and up to 40 $kA/cm^2/\mu s$ of di/dt can be obtained. Therefore, MAGT is a very promising device to replace thyratrons in a high repetition excimer laser system.

REFERENCES

(1) B.W.Scharf and J.D.Plummer, "A MOS-Controlled triac device," ISSCC Tech. Dig., pp.222-223, 1978.
(2) B.J.Baliga, M.S.Adler, P.V.Gray, R.P.Love, and N.Zommer, "The insulated gate rectifier (IGR): A new power switching device," IEDM Tech. Dig., pp.264-267, 1982.
(3) J.P.Russell, A.M.Goodman, L.A.Goodman, and J.M.Neilson, "The COMFET-A new high conductance MOS-gated device," IEEE Electron Device Lett., vol.EDL-4, March 1983.
(4) A.Nakagawa, H.Ohashi, and T.Tsukakoshi, "High voltage bipolar-mode MOSFET with high current capability," Ext. Abst. 16th Conf. Solid-State Devices Mater., pp.309-312, 1984.
(5) A.Nakagawa, Y.Yamaguchi, K.Watanabe, H.Ohashi, and M.Kurata, "Experimental and numerical study of non-latch-up bipolar-mode MOSFET characteristics," IEDM Tech. Dig., pp.150-153, 1985.
(6) A.Nakagawa, K.Watanabe, Y.Yamaguchi, H.Ohashi, and K.Furukawa, "1800 V bipolar-mode MOSFETs: a first application of silicon wafer direct bonding (SDB) technique to a power device," IEDM Tech. Dig., pp.122-125, 1986.
(7) A.Nakagawa, Y.Yamaguchi, K.Watanabe, and H.Ohashi, "Safe operating area for 1200-V nonlatchup bipolar-mode MOSFETs," IEEE Trans. Electron Devices, vol.ED-34, pp.351-355, 1987.
(8) A.Nakagawa, Y.Yamaguchi, and K.Watanabe, "Improved bipolar-mode MOSFETs (IGBT) with self-aligning technique and wafer bonding (SDB) - Why is the bipolar-mode MOSFET SOA large ? -," Ext. Abst. 19th Conf. Solid-State Devices Mater., pp.43-46, 1987.
(9) M.Hideshima, T.Kuramoto, and A.Nakagawa, "1000 V 300 A bipolar-mode MOSFET (IGBT) module," Proc. of 1988 International Symposium on Power Semiconductor Devices (ISPSD), Tokyo, pp.80-85, 1988.
(10)V.A.K.Temple, "MOS controlled thyristors(MCTs)," IEDM Tech. Dig., pp.282-285, 1984.
(11)M.Stoisiek and H.Strack, "MOS GTO - a turn-off thyristor with MOS-controlled emitter shorts," IEDM Tech. Dig., pp.158-161, 1985.
(12)B.J.Baliga, "Enhancement and depletion-mode vertical-channel M.O.S. gated thyristors," Electron. Lett., vol.15, pp.645-647, 1979.
(13)L.Leipold, W.Baumgartner, W.Ladenhauf, and J.P.Stengl, "A FET-controlled thyristor in SIPMOS technology," IEDM Tech. Dig., pp.79-82, 1980.
(14)E.Baudelot, J.P.Chante, and J.J.Urgell, "Improvement of on-resistance of MOS-gated Devices," Electron. Lett., vol.18, pp.546-547, 1982.
(15)W.Seifert and A.A.Jaecklin, "An FET-driven power thyristor," IEEE Trans. Electron Devices, vol.ED-34, pp.1170-1176, 1987.
(16)J.C.Driscoll, "High current, fast turn-on pulse generation using thyristors," IEEE PESC Rec., pp.51-60, 1974.
(17)J.L.Hudgins and W.M.Portnoy, "High di/dt pulse switching of thyristors," IEEE Trans. Power Electronics, vol.PE-2, pp.143-148, 1987.
(18)S.Sugawara and K.Yoshioka, "Regarding to the capability endurable to di/dt of static induction thyristor," Toyo Denki Giho, vol.69, pp.2-6, 1987.
(19)K.Okamura, Y.Watanabe, I.Ohshima, and S.Yanabu, "High-speed, high-power switching of semiconductor devices," IEEE 7th Pulsed Power Conf., 1989, to be published.
(20)K.Watanabe, A.Nakagawa, and H.Ohashi, "Design optimization of 1000 V resistive field plate," Trans. IECE of Japan, vol.E69, pp.246-247,April 1986.