Low ON-State Voltage Optically Triggered Power Transistor for SiC Emitter Turn-OFF Thyristor

Alireza Mojab, *Student Member, IEEE*, and Sudip K. Mazumder, *Senior Member, IEEE*

***Abstract*— In this letter, a new optically triggered power transistor (OTPT) rated for 100-A load current is proposed. Moreover, some modifications in the base epitaxial layer are made to reduce both the ON-state voltage drop and the required optical power for the driving laser. This new structure benefits the fact that increasing the leakage current yields to a lower ON-state voltage in power semiconductor devices (PSDs). Although the proposed structure has a higher leakage current during the OFF-state, the high leakage current is blocked by a high-power low-leakage SiC thyristor that is connected in series with the proposed OTPT. Therefore, one can use the advantage of a rather leaky OTPT to further decrease the ON-state voltage. ON-state voltage drop of 0.8 V is achieved across the proposed OTPT in operating condition of 100 A and 100 °C while it is illuminated by optical power of 5 W. The proposed OTPT, respectively, features 22% and 92% improvement in the textscon-state voltage drop at optical powers of 5 and 2 W, as compared with the conventional low-leakage OTPT.**

***Index Terms*— Optically-triggered power transistor (OTPT), emitter turn-off thyristor (ETO), on-state voltage, leakage current, on-state power loss, optical power loss.**

I. INTRODUCTION

AS THE trend of power electronics industry moves toward high-voltage, high-current and high-frequency applications, keeping the switching-transition and on-state power losses of PSDs in an acceptable level, become more and more challenging. ETOs are one of the most promising devices to handle high supply voltage with reduced number of series PSDs [1]–[3]. Introduction of the optically-triggered (OT) ETOs results in the elimination of the low-voltage control bias, yields to a single-bias ETO and precludes the EMI noise susceptibility.

The first generation of OT ETOs is proposed in [4]–[6]. The presented OT ETO implements one stage of optical device for the OTPT and has a low-current-handling capability in orders of several amperes. This drawback is due to the small active area of the OTPT as a single chip. Therefore, a Darlington configuration for the OTPT is presented to increase the current-carrying capability of the OT ETO. Schematic diagram of the single-biased OT ETO along with the Darlington OTPT, as the optical controlling switch, are shown in Fig.1.

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The authors are with the Laboratory for Energy and Switching-Electronics Systems, Department of Electrical and Computer Engineering, The University of Illinois at Chicago, Chicago, IL 60607 USA (e-mail: mazumder@uic.edu).

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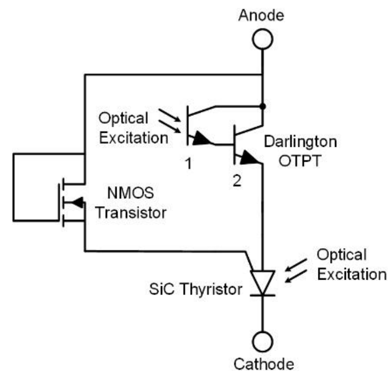

Fig. 1. Schematic diagram of the single-bias all optically-triggered ETO.

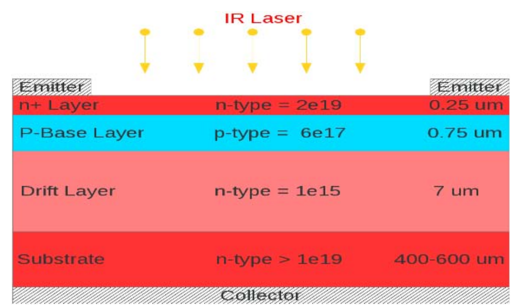

Fig. 2. Cross section of the optical device in the first stage of the OTPT.

The NMOS Transistor is connected in a diode-configuration in the gate path of the SiC Thyristor. More details for the OT ETO have been provided in [5]. Implementing the Darlington configuration, however, results in a higher on-state voltage as compared with the single-stage configuration.

The leakage current of the OT ETO mainly depends on the leakage current of the SiC Thyristor. Therefore, the leakage current of the OTPT can be safely increased to attain a lower on-state voltage at the same optical power. In contrast to the conventional low-leakage OTPT, one can reduce the optical intensity to as low as 2W without a significant change in the on-state voltage.

II. DESIGN STRATEGIES FOR THE DARLINGTON OTPT

The first stage of the Darlington OTPT is a silicon optical BJT that is triggered by an 808 nm laser. The epitaxial layer structure of the optical BJT is shown in Fig. 2. When it is illuminated by laser, a substantial amount of photogenerated electron-hole pairs in the P-Base Layer, convert this blocking layer into conducting layer. The lower doping density and smaller thickness for the P-Base Layer results in lower on-state voltage and faster turn-on behavior. However, the

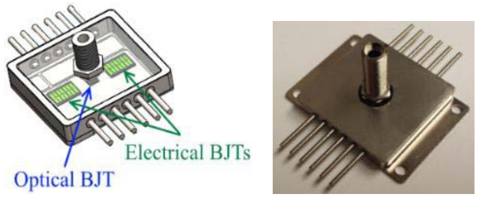

Fig. 3. Fabricated Darlington OTPT in one package.

leakage current and turn-off delay increases. In the second stage of the Darlington OTPT, there is two 50-A identical silicon electrical BJTs in parallel to make it possible for 100-A load current. They have exactly the same epitaxial layer structure as the first optical device shown in Fig. 2. Having the same epitaxial layer, makes it possible for fabricating integrated Darlington structure to reduce the parasitic inductances and unnecessary packaging spaces. In Fig. 3, the fabricated Darlington OTPT is shown.

While increasing the load current, there is a trade-off between faster rise time and lower on-state voltage in one hand and the lower leakage current and faster turn-off on the other hand. A new optimized structure for the OTPT is proposed to achieve an acceptable low on-state voltage. The larger leakage current and slower turn-off are then compensated by the series SiC Thyristor which is designed to have a low leakage current and fast turn-off [7]. Results obtained from Silvaco device and mix-mode simulations prove the accuracy of the new proposed structure.

The most important epitaxial layer for blocking the current in the Darlington OTPT is the P-Base Layer in both optical and electrical BJTs. The P-Base Layer has the highest effect on leakage current and on-state voltage of the OTPT. The doping level of the P-Base Layer is slightly decreased from the previous conventionally used value of 8×10^{17} cm^{-3} to the new optimized value of 6×10^{17} cm^{-3} to make the OTPT device a little leakier. Furthermore, the thickness of the P-Base Layer is decreased from 1.25 μm to 0.75 μm. These decrements result in the reduction of on-state voltage from 1.02 V to 0.8 V that is about 20% smaller. Moreover with the new structure, lower optical intensity is required for the driving laser to achieve the same on-state voltage across the OTPT. Previously, optical power of 5 W was used for the single OTPT, but now an optical power of 2 W is enough to switch the Darlington OTPT into conducting mode. Consequently, the proposed structure introduces both less electrical and less optical power losses.

III. Results and Discussion

The voltage across the Darlington OTPT equals to the sum of the voltages across collector-emitter of the optical BJT in the first stage (V_{CE1}), and base-emitter voltage of the electrical BJT in the second stage (V_{BE2}) of the Darlington OTPT as shown in Fig. 1. V_{BE2} is usually found to be about 0.7 V under most of the conditions. However, V_{CE1} is a function of both the optical power of the laser beam and the layer characteristics of the device itself, especially the doping concentration and thickness of the P-Base Layer. In this letter, by reducing both the thickness and doping level of the P-Base Layer in both optical and electrical BJTs, V_{BE2} is almost remained unchanged, but V_{CE1} is considerably reduced. In Fig. 4, the OTPT on-state voltage and turn-off delay is plotted versus the doping concentration of the P-Base Layer. Similar curve is obtained by varying the P-Base Layer thickness. We decreased both the doping level and thickness of the P-Base Layer until the turn-off delay is kept less than 250 ns. At this point, under an optical power of 5 W and a temperature of 100 °C, the on-state voltage is about 0.8 V and the off-state leakage current is 12 mA.

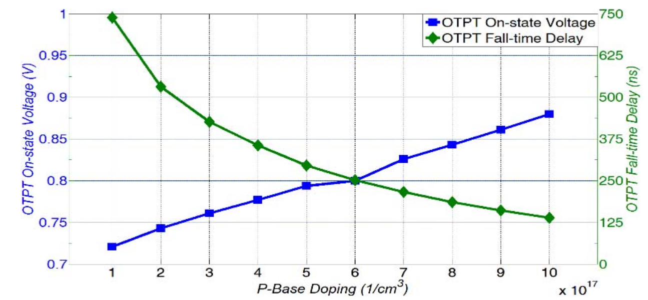

Fig. 4. OTPT on-state voltage and turn-off delay versus P-Base Layer doping (The OTPT P-Base Layer thickness is 0.75 μm).

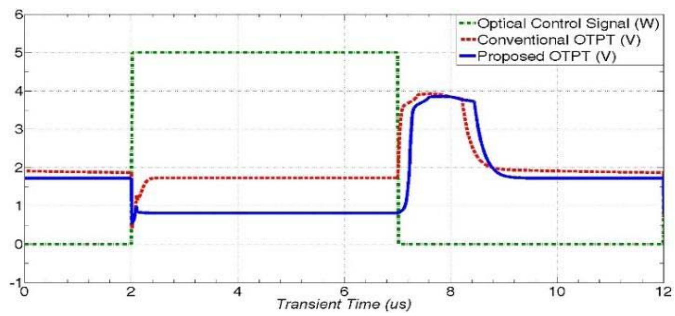

Fig. 5. Transient voltage across the Darlington OTPT for both conventional and proposed structures under optical power of 5 W.

Switching behavior for the voltage across the Darlington OTPT in OT ETO configuration is shown in Fig. 5. These results are obtained at triggering optical power of 5 W. It is shown that the on-state voltage is considerably reduced using the new structure. Although the turn-off delay of the conventional OTPT is 200 ns less than the proposed method, one can use the reduced optical power of 2 W for the new optimized structure to compensate this higher turn-off delay and decrease it by 100 ns. It is worthy to note that on-state voltage is kept at 0.9 V while using the optical power of 2 W. The interesting feature of low on-state voltage in low optical intensities, results in lower optical power loss, as well as, faster turn-on switching action.

The on-state voltage versus optical power for both conventional and new proposed OTPT is shown in Fig. 6. At optical power of 5 W, the on-state voltage is reduced from 1.02 V for the conventional structure to 0.8 V for the proposed structure achieving 22% improvement. On the other hand, the on-state voltage for the proposed structure is 0.9 V at optical power of 2 W, while the conventional structure fails to show any promising conduction (92% improvement).

The reason of having low on-state voltage in the new optimized structure can be attributed to the high current gain

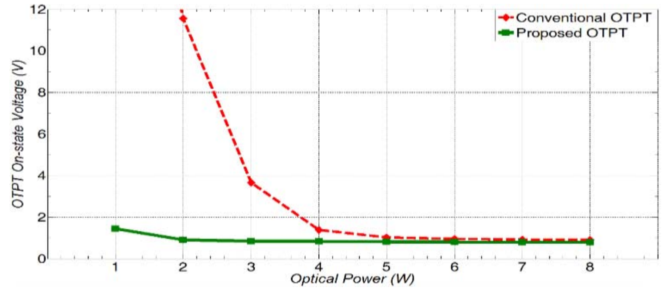

Fig. 6. Darlington OTPT on-state voltage versus laser optical power.

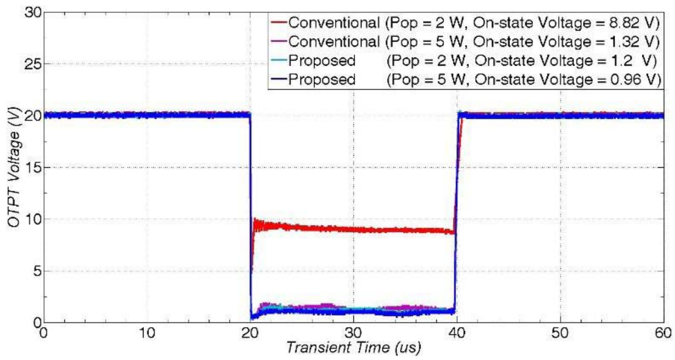

Fig. 7. Experimental results for the voltage across the two fabricated OTPTs under optical powers of 2 W and 5 W.

of the optical BJT which is defined by [8]:

$$\beta = \frac{1}{\frac{D_E N_B W}{D_B N_E L_E} + \frac{1}{2}\left(\frac{W}{L_B}\right)^2} \quad (1)$$

in which D_B, N_B, L_B and W is diffusion coefficient, doping concentration, diffusion length and width of the P-Base Layer respectively. By decreasing N_B and W, higher current gain and hence lower on-state voltage is achieved. In Fig. 7, the experimental results of the voltage across two different fabricated OTPTs for a switching frequency of 10 kHz are shown. The conventional fabricated OTPT has a P-Base Layer with a thickness of 1.4 μm and a doping concentration of 6×10^{17} cm^{-3}. The conventional OTPT shows an on-state voltage of 1.32 V and 8.82 V under optical powers of 5 W and 2 W respectively. For the proposed fabricated OTPT, the P-Base Layer thickness and doping concentration is 0.85 um and 5.5×10^{17} cm^{-3}. The on-state voltage for the new fabricated OTPT is 0.96 V and 1.2 V under optical power of 5 W and 2 W respectively. As shown, the conventional OTPT has poor conductivity under illumination of 2 W.

As mentioned in the previous section, the new modified Darlington OTPT has higher leakage current compared to the previously designed structure. The leakage current is increased from 3 mA for the conventional structure to 12 mA for the new proposed structure. However, this increased leakage current makes no problem for the proposed OT ETO structure. The reason is that the leakage current is blocked by the series-connected low-leakage SiC Thyristor and is found to be about 300 μA during the ETO off-state. In Fig. 8, the on-state voltage and off-state leakage current for the complete ETO structure of Fig. 1 is plotted versus the thickness of the P-Base Layer of the OTPT. Similar plot is obtained for the

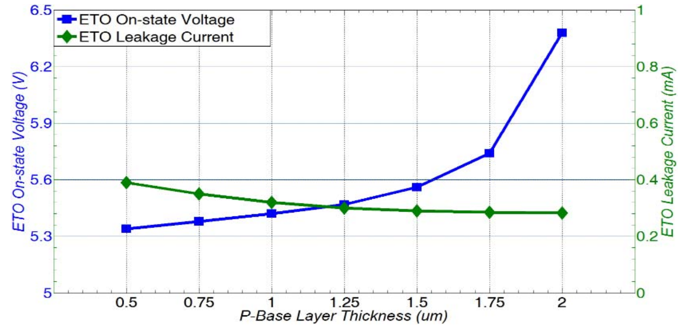

Fig. 8. ETO on-state voltage and leakage current versus P-Base Layer thickness (The OTPT P-Base Layer doping is 6×10^{17} cm^{-3}).

variation of P-Base Layer doping level. As shown, the new OTPT design introduces considerably lower on-state voltage and hence lower power loss during the ETO on-state, while keeping low off-state leakage current. Experimental results done by Tektronix 371A show a leakage current of about 18 mA for the proposed OTPT under bias voltage of 50 V, while it is 7 mA for the conventional OTPT.

IV. Conclusion

A new Darlington optically-triggered power transistor (OTPT) was proposed in this letter as an auxiliary switch for an optically-triggered emitter turn-off (ETO) thyristor rated for current of 100 A. In contrast to the conventional solution, the proposed OTPT has lower on-state voltage while lower optical power of about 2 W is required to trigger the OTPT. Therefore, the proposed structure introduces both lower electrical and optical power losses. However, these attractive features are achieved by sacrificing the leakage current. Therefore, the proposed OTPT cannot be used as a stand-alone device for other typical applications. However, it is beneficial to use it as a high-power switch in the optically-triggered ETO thyristor because the leakage current is blocked by the series-connected SiC Thyristor in the OT ETO structure.

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