Design and Characterization of High-Current Optical Darlington Transistor for Pulsed-Power Applications

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Abstract—A high-current and low on-state voltage optical Darlington transistor (ODT) is developed in this paper for high-power applications. The structure of this device includes a two-stage Darlington transistor in which the first stage is triggered optically using an infrared laser of an 808-nm wavelength. The photogenerated current in the first stage drives the second stage of the ODT for current amplification. The ON-state voltage of the proposed two-stage ODT is found to be 1.12 V at 50 A. The results show that a single-pipe laser with a low optical power of 2 W is sufficient to trigger this high-current optical switch. This can give us more flexibility to achieve an optimal tradeoff between the ON-state voltage and delay times. The experimental results show that the ODT has a breakdown voltage of 70 V and can operate at frequencies higher than 10 kHz. This makes it potentially suitable as an optical gate driver for applications including but not limited to pulsed-power and series-connection of power semiconductor devices for voltage scaling, and as an auxiliary optical-triggering device for anode- or even gate-current modulation of a high-frequency and high-power all-optical emitter turn-OFF thyristor.

Index Terms—Long-wavelength laser illumination, optical Darlington transistors (ODTs), series connection of power semiconductor devices, single-bias all-optical emitter turn-OFF (ETO) thyristor, wide-bandgap power semiconductor devices.

I. INTRODUCTION

S UPERIOR advantages of optical links as a triggering mechanism in power semiconductor devices have opened new fields of development for high-power application. These advantages include mitigation of electromagnetic interference (EMI) noise, removal of complex electrical driver circuits, elimination of backpropagation from power to control stage, and conductivity modulation for optical switches through intensity modulation [1], [2]. The design and fabrication of a high-current optically activated power semiconductor

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Optical Darlington Transistor NMOS 2 Transistor UV Laser Anode |↓|↓ P+ Gate Base Ν P-Drift SiC Thyristor Ρ Buffer Substrate N+ Cathode

Fig. 1. Application of ODT for all-optical single-bias ETO thyristors.

switch is outlined in this paper that addresses the reduced optical need for many high-power applications. This highcurrent optical Darlington transistor (ODT) can be used to trigger series-connected power semiconductor devices, such as high-power thyristors, insulated gate bipolar transistors, and BJTs to achieve higher blocking voltages [3], [4]. The advantage of using optical driver for series-connected devices is the substitution of complicated electrical gate drivers with simpler optical laser drivers.

All-optical single-biased emitter turn-off (ETO) thyristor is another interesting application for this designed ODT as a newly proposed technology for fully controllable thyristors [1]. Here, instead of being used in optical driver, the optical switch is placed in series with the main high-power thyristor, as shown in Fig. 1; therefore, the optical switch should be capable of handling the high rated current of the optical SiC thyristor. Electrical ETO thyristors have been already developed to facilitate more reliable options in high-power thyristors for highvoltage switching applications [5]-[7]. These applications include but not limited to: high-voltage ETO thyristor-based dc breakers [8], [9], ETO-based high-power converters [10], flexible ac transmission systems (FACTS) [11], wind power systems [12], and pulsed power applications [13]. ETOs have been shown to achieve better turn-ON and turn-OFF controllability, using two MOSFET transistors to assist the switching transition of the main high-power thyristor [7].

Furthermore, ETOs benefit a turn-OFF snubberless solution [14] for mitigating high di/dt or dv/dt problems associated with the previous counterparts like gate turn-OFF [15], [16] and MOS turn-OFF thyristors [17] along the lines of integrated gate-commutated thyristors [18], [19]. However, all of the above-mentioned electrically triggered high-power thyristors, including electrical ETOs, can be susceptible to EMI noise [20], [21].

Optical ETO thyristors have been then introduced in [1] and [22] to overcome the EMI noise effect and deliver a single-biased technology for high-power thyristors. Optical links are immune to EMI noise and enable conductivity modulation by changing the optical intensity. In the configuration of optical ETOs proposed in [22], a single-device optical switch is used in which the most important issue is the limited maximum current capability of the optical chip up to about 10 A. The current rating for the fabricated optical SiC thyristor by Cree Inc. introduced in [23], which is used in optical ETO application, is reported to be at least 28 A. Therefore, an optical switch with higher current-carrying capability is required to facilitate the high-power switching action of the optical ETOs. Since the optical illumination is narrowed to only one laser fiber with a diameter of 1 mm or less, a single-chip optical switch cannot be used for higher current ratings. In [24], a high-current optical ETO is proposed in which a two-stage ODT is used as the series optical switch. However, no experimental results are reported in [24] and only analytical and simulation results are provided. In this paper, high-current experimental results along with the design and fabrication steps for the high-current ODT are provided in more details.

For low-current applications less than 10 A [25]-[28], a single-stage optical device is designed and fabricated in this paper. The current capability for single-stage optical device is limited, since the optical illumination is narrowed to only one laser fiber with a diameter of 1 mm or less. Several optical device dies with different area sizes of 1, 4, 9, 16, and 25 mm² have been designed and fabricated, but for all the dies, only a circle of about 1 mm² is illuminated by the IR laser with 1-mm fiber diameter. Experimental and simulation results show that higher leakage current and longer rise and fall times are obtained for larger dies. Hence, the optimized die size is the 4 mm^2 one along with using a laser fiber of 1-mm diameter, considering compensation due to misalignment between the center of fiber tip and the center of die substrate. Moreover, the gap between the fiber tip and the die substrate (about 3 mm) results in optical illumination expansion out of the fiber tip, which is related to the numerical aperture of the laser optical fiber. Therefore, the optimal die size is bigger than the 1-mm² area size.

For high-current applications, a maximum current rating of 50 A is investigated for the ODT. A single optical device is not sufficient to tolerate this high current rating. Therefore, it is connected with another electrical BJT in a Darlington configuration as shown in Fig. 2 to obtain high-current capability of 50 A. Several electrical BJTs connected in parallel can be used in the second stage of the ODT based on the tradeoff between ON-state voltage and switching speed requirements.



Fig. 2. (a) Equivalent circuit and (b) device layers for the high-current two-stage ODT.



Fig. 3. Cross section of the optical device in the first stage of the high-current ODT.

In this paper, two electrical BJTs in parallel are used for the second stage of the ODT. Each of the electrical BJTs supports half of the total rated current of 50 A; however, the surge current for each electrical BJT is about 50 A. The fabrication steps and packaging of this ODT are provided in the follow-up sections.

II. DEVICE STRUCTURE, LAYOUT, AND FABRICATION

In this section, the device structure and fabrication steps for the ODT are provided. The epitaxial layers for both the optical device and the electrical BJTs in the ODT are identical to enable the possibility of an integrated structure. The firststage optical device is a two-terminal device with collector and emitter contacts, while the second-stage electrical BJTs are three-terminal devices with additional base implantation and metallization to form the base contact in addition to collector and emitter contacts. The photogenerated current from emitter contact of the optical device is pushed into the base contact of the electrical BJTs for current amplification.

A. Epitaxial Layers Structure for the Optical Device

In Fig. 3, schematic epitaxial layers grown by chemical vapor deposition is shown, which is designed and optimized for both of the optical and electrical devices in the Darlington



Fig. 4. Carrier concentration profile along the epitaxial layers measured by SRP.

structure for a rated current of 50 A. The substrate layer is a highly doped n⁺ type silicon wafer with a thickness of about 650 μ m and a doping concentration of 2 × 10¹⁹ cm⁻³. The substrate wafer has a plane orientation of (100) and is doped with arsenic (As) with a resistivity of less than 0.005 Ω -cm. For better surface quality and uniformity, a buffer layer with the same doping concentration as the substrate layer is deposited first. Then, a thick drift layer doped lightly with phosphorus is grown on the substrate to form the blocking layer for high-voltage applications. The doping concentration and the thickness of the drift layer are set at 1×10^{15} cm⁻³ and 7 μ m, respectively. These characteristics are designed to achieve a breakdown voltage of at least 70 V. Increasing the thickness of the drift layer or decreasing its doping level results in higher breakdown voltage, but at the cost of higher ON-state voltage for the ODT.

A p-type layer doped with boron as the p-base layer is then grown on the drift layer. The doping concentration and the thickness of the p-base layer are 6×10^{17} cm⁻³ and 0.75 μ m, respectively. This layer is optimized to obtain the best possible conductivity and delay times. Increasing the doping level or thickness of the p-base layer results in a lower fall time, but, at the cost of higher ON-state voltage. Finally, a highly doped n-type layer is grown on the p-base layer to form the emitter n^+ layer of the optical device. The doping concentration and the thickness of this layer are 2×10^{19} cm⁻³ and 0.25 μ m, respectively. The n⁺ layer doped heavily with phosphorus yields an excellent ohmic contact to the upper emitter terminals. This layer also provides a low-resistive path for lateral transfer of photogenerated carries with a small surface recombination velocity. The doping profile along the epitaxial layers of the optical device measured by spreading resistance probe is shown in Fig. 4.

B. Metallization and Surface Layout for the Optical Device

After the epitaxial layers are grown, a metal stack is deposited on the top n^+ layer to form emitter contacts. Then, the same metallization is implemented on the wafer backside for collector contact. The metal stack is deposited



Fig. 5. Top view of the optical device layout in the first stage of the ODT.

with titanium (Ti), platinum (Pt), and gold (Au). The e-beam evaporation system is used in room temperature to deposit Ti, Pt, and Au with the respective thicknesses of 20, 40, and 4 μ m, respectively. Gold is used for better conductivity suitable for high-current capability and titanium is used for better adhesion to silicon. Platinum is used as a buffer metal between titanium and gold layers.

The first photolithography mask is then used for patterning the upper metal layer to form the emitter contacts. The metal stack is removed from the device surface by the liftoff technique. In Fig. 5, a top view of a circular layout for the optical device is shown. Since the laser fiber is circular, using circular pattern for the optical device can reduce the total device area by covering the unilluminated corners as emitter contact pads. As the device inactive area is decreased, the stray and parasitic capacitances of the device and layout are decreased as well. This will in turn increase the device switching speed by reducing the delay times. Furthermore, by providing four emitter pads in the corners of the circular layout, the photogenerated charge carriers are collected into the emitter terminal uniformly all over the device surface.

The total optical device area is 4 mm^2 , as shown in Fig. 5 and the active illumination area for the IR laser is about 3.14 mm². The width of top emitter fingers in the illumination area for the optical device is 4 μ m, as shown in Fig. 3. The width of the emitter finger is designed based on the conductivity of deposited gold for a maximum current capability of 10 A for the first optical device of the Darlington structure. The separation between the top emitter fingers in the illumination area is about 60 μ m on average. In one side, longer distance between emitter contacts results in poor charge carrier collection after being generated by the IR Laser. Furthermore, carrier recombination rate is increased due to longer distance for holes to reach the emitter contacts. On the other side, shorter distance between emitter contacts will increase the top surface metal covering. This results in more surface shading against laser illumination and consequently, less photogenertion of electron-hole in the optical device. Silvaco software (the 2-D process and device simulator [29])



Fig. 6. Cross section of the electrical BJTs in the second stage of the ODT.

is used to find the optimum separation between the top emitter contacts.

C. Boron Implantation and Base Contact for Electrical BJTs

The epitaxial layers structure and the doping profile for electrical BJTs are the same as optical device shown in Fig. 3. The only difference in the fabrication steps for these two electrical BJTs is the formation of base contact. The identical epitaxial layers for both optical and electrical devices provide us the possibility of fabricating an integrated ODT in which both devices are implemented in the same die. This option can reduce the parasitic inductances of the wirings between the two devices. However, in this paper, several dies with different area sizes for both optical and electrical devices are designed and fabricated separately. This provides the flexibility to further explore the different combination of these devices for different electrical and optical power ratings. In this hybrid configuration, one can aim for the desired rated current for the ODT by connecting the required number of electrical BJTs in parallel and then use the required laser power for the optical device to provide the appropriate driving current into the base terminals of the electrical BJTs connected in parallel.

Before carrying out the metallization and surface-layout patterning for the electrical BJT, two photolithography steps are performed to form the p^+ layer, as shown in Fig. 6. First, the top emitter n^+ layer is etched in the regions of base contact fingers through the first mask and lithography. The etchant used in this step is 30% potassium hydroxide (KOH) with an etch rate of 0.7 μ m/min. About 0.4 μ m of silicon is etched to make sure the n^+ layer is completely removed. The etched area between two consecutive remained n⁺ layers is 14 μ m. Subsequently, the second lithography is implemented to open the required windows in the photoresist for doing the boron implantation. Boron is implanted into the p-base layer with a width of 8 μ m. Next, a three-step ion implantation is performed with implantation doses of 2.1×10^{15} , 1.5×10^{15} , and 1×10^{15} cm⁻². The corresponding implantation energies are 85, 50, and 20 keV, respectively. Then, the wafer samples undergo a rapid thermal annealing process with a temperature of 1000 °C within 12 s to form the p^+ layer.



Fig. 7. Top view SEM picture of the electrical BJT layout in the second stage of the ODT.

The metallization for the electrical BJT samples are carried out simultaneously with the optical-device samples. Similarly, metal stacks of Ti, Pt, and Au with the respective thicknesses of 20 nm, 40 nm, and 4 μ m are deposited on both sides of the wafers. Subsequently, a top surface layout patterning is implemented through the third mask and lithography for electrical BJTs to separate the metals of base and emitter contact fingers. The width of the base and emitter contact fingers is 6 and 8 μ m, respectively, as shown in Fig. 6. The widths of these fingers are calculated based on the conductivity of gold (which at room temperature is about 4.1×10^7 S/m) to support a maximum current of 10 A for base fingers and 50 A for emitter fingers. Fig. 7 shows a scanning electron microscopy (SEM) top view of the base and emitter fingers close to emitter pad. The boron implanted regions can be seen as light shadow areas around the base fingers.

D. Device Edge-Termination Technique and Passivation

In order to obtain the desired breakdown voltage, the edge of the device dies should be perfectly diced. Since the cutting blade of the dicing machine is not perfect and there is always damage to the wafer crystal in the dicing path, critical electric field builds up in those area and cause earlier breakdown. Some records from the previous fabricated devices show that for similar devices without proper edge termination, the breakdown voltage was reduced to about 20–30 V.

For the fabricated devices shown in this paper, a bevel edge is formed around the device chips as shown in Fig. 3 for the optical device. This step is performed using another mask and lithography step to etch the silicon all through the n^+ layer and p-base layer and about 2 μ m deep into the drift layer. The etchant used here was potassium hydroxide (KOH) solution, which removes the silicon with plane orientation of (100) by an angle of about 55°. The bevel edge termination technique [30] is also implemented on the electrical BJT dies, which is not shown in Fig. 6.

Passivation of the devices is implemented by nitride (SiN_x) deposition over the entire wafer surface. For the electrical BJTs, a nitride layer of 0.2–1 μ m is enough for the surface passivation. One technique to maximize the optical absorption



Fig. 8. Prototype package for the 50-A ODT.

in optical devices is to deposit an antireflection coating (ARC) layer on top of the surface, which is a typical step for fabricating solar cells and photodetectors. The nitride layer on the proposed optical device in this paper can play the role of both passivation and ARC layers. The optimized refractive index (RI) and thickness of the nitride layer as ARC layer can be found using [29]

$$n_{\rm ARC} = \sqrt{n_0 n_s} \tag{1}$$

$$d_{\rm ARC} = \frac{\lambda}{4n_{\rm ARC}} \tag{2}$$

in which n_0 and n_s are the RI of air and silicon, respectively. λ is the wavelength of incident light, which is set at 808 nm (the wavelength of the IR laser) and the corresponding n_s is found to be 3.686. Using (1) and (2), the optimal RI and the thickness for the nitride layer are determined to be 1.92 and 105 nm, respectively.

III. PACKAGING AND EXPERIMENTAL SETUP

A specific package with a built-in window to mount the laser fiber is used for the fabricated ODT. Before putting the dies on the package, the final mask and lithography step is implemented to form the vias on the passivation layer (nitride) on the contact pads. Via etch is implemented using buffered hydrofluoric acid as the etchant. Then, the dies are placed on the package in which the backside of the dies is connected to the substrate of the package to form the collector contact. A picture of the 50-A ODT package is shown in Fig. 8 in which one optical device die and two electrical BJT dies in parallel are placed in this package. The dimensions of the package are $3.3 \text{ cm} \times 3.4 \text{ cm}$. The optical device die is placed on collector pad in the middle of package, and the two



Fig. 9. Experimental setup for the ODT at a load current of 50 A.

electrical BJTs are placed on the same collector pad on the right and left sides of the optical device.

Wire-bonding technique is used to connect the emitter contacts of the optical device to the base contacts of the two electrical BJTs. For this purpose, 5-mil aluminum wire bonds are used. There are totally four wire bonds on the optical device extracted out from the four emitter pads in the corners of the optical device (Fig. 5) to the base contact of the electrical BJTs (two wire bonds to each of them), as shown in Fig. 8. The same wire-bonding technique is used to connect the emitter contacts of the electrical BJTs to the emitter pad of the package, with the exception that 10-mil aluminum wire bonds are used for higher current capability. A total number of 16 wire bonds from each) to the emitter pad of the package.

To observe and measure the voltage of the base contact in the ODT, one 10-mil aluminum wire bond is used to connect the base contact of one of the electrical BJTs on the right to the base pad of the package. Finally, 10-mil aluminum wire bonds are used to connect the pads to the corresponding terminal pins, as shown in Fig. 8. There is one pin for the base terminal, five pins for the emitter terminal and six pins for the collector terminal.

At last, the package lid, which includes a standard SMA 905 connector for mounting the laser fiber, is placed on the package. The complete test bench for the ODT along with the IR laser and laser driver is shown in Fig. 9. The IR laser used to trigger the ODT is a Photontec Berlin laser [31] with a central wavelength of 808 ± 10 nm. The maximum fiber output power is 7.04 W under an operating current of 9.04 A and a threshold current of 1.59 A. Linear interpolation is used to find the approximate driving current for the required output power of the laser. The following equation is used to find the required to find the approximate for the laser driver:

$$i_{\text{Laser}}(A) = \frac{9.04 - 1.59}{7.04} P_{\text{laser}}(W) + 1.59.$$
 (3)

The IR laser used in the experiments has the capability to be connected to different optical fibers with different diameter sizes through the standard SMA 905 connector. Several optical fibers with different diameter sizes of 200, 400, 600, and 1000 μ m have been used and connected between



Fig. 10. Voltage across the ODT operated in all-optical ETO configuration.

the laser and the ODT package. The results obtained based upon switching-transition and ON-state voltage measurements, using each of the different optical fibers show that the lowest ON-state voltage is achieved using the $1000-\mu$ m optical fiber. This 1-mm fiber diameter is the maximum available one and all the experimental results provided in Section IV is obtained using the 1-mm optical fiber. Larger optical fiber diameters may be used to obtain better results. The laser driver used to trigger the 808-nm laser is DEI PCX-7410 laser diode driver with a maximum driving current of 10 A. The switching frequency and the duty cycle is set at 10 kHz and 20%, respectively, for the experiments.

IV. RESULTS AND DISCUSSION

The experimental setup for the ODT is prepared to emulate its use for industrial pulsed-power applications outlined in Section I. For series-connected power devices, a low bias of 5-10 V is enough for the ODT. For the application of optically triggered single-biased ETO thyristor shown in Fig. 1, Silvaco TCAD simulations have been performed to find the maximum voltage drop across the optical switch. The results show that the maximum ON-state and OFF-state voltage drop across the ODT is 0.8 and 3.2 V, respectively. In other words, there is no high-voltage stress on the ODT in the ETO configuration as almost all the bias voltage is blocked by the SiC Thyristor. The Silvaco simulation results for voltage across the ODT operated in the ETO configuration are shown in Fig. 10 for one switching cycle at a load current of 50 A. The parasitic inductances in anode and gate loops of the SiC thyristor is assumed to be 3 nH in these simulations, which results in an overshoot voltage of 8.3 V on the ODT when the ETO is turned OFF. The results given in this section is provided for the single optical device separately at a maximum current of 10 A, and then for the complete ODT at a maximum current of 50 A.

A. Optical Device (First Stage of the Darlington Structure)

The optical device in the first stage of the Darlington structure is designed for a maximum current of 10 A.



Fig. 11. Optical device collector current versus collector voltage for different optical powers (measured by Tektronix 371A).

However, the maximum surge current can be as high as 15 A depending on the designed layout of the top emitter contacts in the optical device and the packaging and wire-bonding techniques. If the current requirement for the optical-switch application is limited to 10 A, the single optical device is enough and there is no need to use the Darlington structure. In this way, one can use the benefit of lowest possible ON-state voltage and parasitic inductances of the single optical device separately in the package of Fig. 8, the single base terminal is used, which is connected to the emitter of the optical device.

For the optical characterization, this base terminal is grounded and the collector terminal is swept between 0 to 10 V under different optical powers. The I-V family curves measured by the Tektronix 371A curve tracer for the optical device when illuminated at varying optical power using a 808-nm wavelength laser is shown in Fig. 11. As shown, by increasing the optical power, the current is increased which is due to more photo-generated electron–hole at higher optical powers in the base layer of the optical device. One can take the advantage of the conductivity modulation in the optical device due to changing optical power of the laser.

For experimentally determining the switching response, a bias voltage of 10 V is connected between the collector and the base terminals of the ODT package to conduct the experiments only on the optical device while the emitter terminals are kept floating. To obtain a 10-A rated current, a load resistance of 1 Ω is used in series with the collector terminal of the ODT. The switching frequency and the duty cycle of the laser-driver are set at 10 kHz and 20%, respectively.

The switching response of the optical device under 5 W of illumination with 808-nm laser is shown in Fig. 12. The ON-state voltage of the optical device is found to be 780 mV. In Fig. 13(a) and (b), the switching dynamics of the optical device, respectively, during its turn-ON and turn-OFF transitions are shown. The rise and fall times of the optical device current are found to be 94 and 411 ns, respectively. The corresponding fall and rise times for the optical device voltage are found to be 73 and 397 ns, respectively. Rise time is considered to be the time from 10% to 90% of final value



Fig. 12. Switching response of the optical device at a current of 10 A, an optical power of 5 W, and a frequency of 10 kHz.

of the current or voltage. Similarly, fall time is considered to be from 90% to 10% of initial value of the current or voltage. The optical device exhibits a rapid turn-ON transition resulting in a very small turn-ON switching loss. On the other hand, the turn-OFF time is found to be longer, which is attributed to the poor turn-OFF behavior of the laser driver, as shown in Fig. 13(b). The turn-ON time and the turn-OFF tail of the laser driver are found to be about 60 ns and 1 μ s, respectively. If a laser driver with shorter fall time is used, reduced fall time and delay in turn-OFF initiation for the optical device is expected. Silvaco TCAD simulations show that for a fast IR laser, rise and fall times of 48 and 243 ns, respectively, are achieved for this optical device.

Optical power density of the laser is one of the important parameters for the fabricated ODT. It is desired to use the lowest possible optical power, which is associated with lower drive current and lower power losses. As the optical power density is decreased, the ON-state voltage of the optical device increases exponentially, while the fall time is reduced appreciably. The measured ON-state voltage and fall time for the optical device under different optical powers at a current of 10 A is shown in Fig. 14. It is noted that, for optical powers of 2 and 1 W, the ON-state voltage is increased up to 4.16 and 7.12 V, respectively, which is considered as unsuccessful switching.

Experimental results show that in order to keep the ON-state voltage less than 1.5 V under a load current of 10 A, we have to use laser optical powers of 4 W and more. Furthermore, by increasing the load current of the single optical device more than 10 A, the ON-state voltage increases significantly. The high ON-state voltage of the optical device at higher currents is attributed to high current density, which is estimated using the Schottky equation for a diode forward voltage as

$$V_{\rm ON} = \frac{nkT}{q} \ln\left(\frac{I_F}{I_0}\right) \tag{4}$$

in which *n* is the quality factor, *k* is Boltzmann's constant, *T* is the absolute temperature, *q* is the electron charge value, I_F is the forward current through the device, and I_0 is the dark saturation current.

It is shown in the next section that using the Darlington structure instead of a single optical device can keep the ON-state voltage less than 1.5 V at higher load currents



Fig. 13. Switching response of the optical device. (a) Turn-ON transition. (b) Turn-OFF transition.



Fig. 14. ON-state voltage and fall time of the optical device versus optical power at a current of 10 A.

up to 50 A. Furthermore, one can use only 1 W of optical power to achieve this low ON-state voltage, which is the most important advantage of this ODT.

B. Two-Stage Optical Darlington Transistor

In this section, the results obtained for the complete two-stage ODT is provided. This time, collector, and emitter terminals of the ODT package shown in Fig. 8 are biased and the base terminal is kept floating. Similar to Fig. 11, optical characterization of the complete two-stage ODT is obtained, which is shown in Fig. 15 for different optical powers.



Fig. 15. ODT collector current versus collector voltage for different optical powers (measured by Tektronix 371A).



Fig. 16. Switching response of the ODT at a current of 50 A, an optical power of 2 W, and a frequency of 10 kHz.

The designed maximum surge current for the two-stage ODT is about 100 A based on the emitter top metallization density of the electrical BJTs and the number of wire bonds used in the prototype package. As shown in Fig. 15, at the collector voltage of 10 V, the optical powers of 1 and 2 W can provide the currents of 46 and 63 A for the ODT, respectively. Therefore, for the purpose of 50-A load current, an optical power of ~ 1.2 W is enough to provide the required low ON-state voltage. This advantage of using lower optical powers for higher rated current is due to current amplification in the two-stage Darlington structure. The rate of increase in collector current as shown in Fig. 15 is not linear and for optical powers of more than 2 W, the maximum available current is saturated up to about 80 A at a collector voltage of 10 V.

To obtain the switching characterization of the ODT, a bias voltage of 10 V is applied between the collector and emitter terminals of the ODT and the base terminal is kept floating. A load resistance of 0.2 Ω is connected in series with the collector terminal to limit the current up to 50 A. The voltage across this resistor is monitored to measure the current through the ODT. The switching response of the two-stage ODT under the illumination of 2 W with 808-nm wavelength is shown in Fig. 16. The ON-state voltage of the two-stage ODT under the illumination of 2 W is found to be 1.28 V, which is considerably lower compared with 4.16 V obtained



Fig. 17. ON-state voltage and rise time of the ODT with varying optical power at a current of 50 A.



Fig. 18. ON-state voltage of the optical device and ODT versus current for optical powers of 2 and 5 W.

for the single optical device shown in Fig. 14. Therefore, using the Darlington structure is not only suitable for high-current applications, but also is efficient to reduce both optical power and ON-state power losses.

The rise and fall times for the ODT at the illumination of 2 W under the load current of 50 A are found to be 330 ns and 3.67 μ s, respectively. For the ODT under high-current operation, increasing the optical power of the laser does not make any considerable change on the fall time, but it reduces the rise time significantly. The ON-state voltage across the ODT and its rise time with varying optical power are shown in Fig. 17 for the load current of 50 A. As shown, the ON-state voltage is decreased from 1.36 V for an optical power of 1 W to 1.08 V for an optical power of 7 W. Similarly, the rise time is decreased from 626 to 235 ns. The fall time of the ODT under an illumination of 7 W and a current of 50 A is found to be 3.75 μ s, which is close to 3.67 μ s obtained for the optical power of 2 W.

The other important factor affecting the ON-state voltage of the ODT is the current density passing through it. By increasing the load current, the ON-state voltage is increased as well exponentially. Fig. 18 shows the experimental results obtained for the ON-state voltage across the optical switch versus rated current for the optical powers of 2 and 5 W. The results for rated currents from 2 to 10 A is obtained by using the single optical device and the results shown for currents from 10 to 50 A are obtained by using the complete Darlington structure.

As shown in Fig. 18, there is a drop in ON-state voltage at the rated current of 10 A as we transfer from the single optical device to two-stage Darlington structure. This drop is especially higher for an optical power of 2 W, which shows the advantage of two-stage Darlington structure over the single optical device for higher current and lower optical power. Even for higher optical power, the rate of increase in the ON-state voltage versus rated current is reduced when transferring from single optical device to two-stage Darlington transistor as shown in Fig. 18 for an optical power of 5 W at the rated current of 10 A.

As a side note, it is worthwhile to mention the conduction loss achieved using the ODT in the context of the all-optical ETO thyristor. In a conventional electrical ETO, an electrically triggered pMOS transistor is used instead of the ODT. The ON-resistance of such a high-current pMOS transistor at the current rating of 50 A is typically about 110 m Ω according to the datasheet. This is corresponding to pMOS conduction loss of \sim 275 W. A voltage drop of 1.28 V is achieved at a load current of 50 A using this introduced ODT, which is indicating an ON-resistance of 25.6 m Ω . Therefore, the conduction loss for the ODT is found to be 64 W, which is about 76% less than that of pMOS transistor. In electrical ETOs, they usually add many pMOS transistors in parallel to reduce the conduction loss. In order to achieve a low conduction loss comparable with that of ODT, at least five pMOS transistors need to be connected in parallel, which increases the total area of the device and may add to drive complexity for current equalization.

The breakdown voltage of the fabricated ODT has been measured using Tektronix 371A curve tracer and is found to be about 70 V. Even though the voltage stress on the ODT operated in the ETO thyristor circuit is always less than 10 V, during ETO turn-OFF, a voltage overshoot is observed on the ODT in Silvaco simulations. This overshoot voltage depends on parasitic inductances of the device packaging and especially the parasitics in the anode and gate loops of the SiC Thyristor. The inductance of the packaged Darlington device is found to be less than 20 nH. Silvaco simulation results show that for the parasitic inductances of 20 nH, the ODT is subjected to an overshoot voltage of 44 V when the ETO turns OFF. In another simulation for the worst scenario, a parasitic inductance of 40 nH is considered for all the connections in ODT, anode, and gate contacts of the SiC Thyristor. The overshoot voltage is found to be 64 V for a parasitic inductance of 40 nH. These results confirm that the fabricated ODT with a breakdown voltage of 70 V and ON-state voltage of about 1.2 V at the current of 50 A is a suitable highcurrent optical device for further applications of all-optical ETO thyristor.

V. CONCLUSION

In this paper, a novel high-current low ON-state voltage and low-loss optically triggered device for applications ranging from industrial pulsed power, to series connection of power semiconductor devices, and all-optical ETO thyristor, has been described. The fabricated ODT includes one optical device driving two electrical BJTs in parallel for current amplification. This optical switch can be triggered with a longwavelength laser with a low optical power of less than 2 W for a rated current of 50 A. The ON-state voltage drop achieved for the ODT at a load current of 50 A is measured to be 1.28 V under an illumination of 2 W. Thus, the ODT reduces both optical triggering power and electrical ON-state power loss. According to the simulation results carried out in Silvaco, higher current ratings up to 100 A can be achieved using higher optical powers for the IR laser or using more electrical BJTs in parallel in the second stage of the ODT. If a larger die with an area of 9 mm² for the optical device in the first stage of the ODT can be used along with an optical fiber with diameter of larger than 1 mm^2 , then a maximum current capability of 200 A is expected to be achieved for this proposed ODT.

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