Optically-Switched Wide-Bandgap Power Semiconductor Devices and Device-Transition Control

S.K. Mazumder, Senior Member, IEEE, A. Mojab and H. RiaziMontazer, Student Members, IEEE
Email: mazumder@uic.edu

Abstract—In this paper, a top-level outline on the work related to optically-switched power semiconductor devices that have been carried out at the University of Illinois, Chicago (UIC) or those in which UIC has been involved has been outlined. In addition, an outline on optical control that affects the switching dynamics of the power semiconductor devices is provided.


I. INTRODUCTION

Optically-triggered power semiconductor devices provide some major advantages over their electrically-triggered counterpart. Such advantages are multi-fold and encompass a) immunity to electromagnetic interference, b) elimination of back-propagation effect from the power stage to the control stage, c) higher reliability due to complete electrical isolation, d) simple realization of gate drive for high power multilevel and series connected device based power-conversion systems, and e) easy controllability of switching dynamics thereby enabling systems control at the device level to name a few. As such, the potential applications of such optically-triggered power semiconductor devices include, fly-by-light (FBL), smart grid, electric vehicles, power-quality conditioners, renewable energy, electromechanical launch systems, and pulsed-power systems. Yet another applicability of such a technology is the ability to control the switching dynamics of both electrically- as well as optically-triggered power semiconductor devices thereby enabling systems control at device level with regard to several performance and reliability parameters including dv/dt and di/dt stress, switching loss, as well as noise mitigation.

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II. OVERVIEW OF PREVIOUSLY ACHIEVEMENTS ON THE OPTICAL POWER SEMICONDUCTORS

A. Optically-Triggered Power Transistor (OTPT) [1]

Our research on optically-triggered power semiconductor switches initiated with a lateral GaAs-based optically-triggered power transistor (OTPT). GaAs has a high level of light absorption and hence a high quantum efficiency. Fig. 1 shows the device structure of the GaAs-based OTPT, micrograph of a prototype OTPT and its packaged realization [1]. The OTPT has a lateral structure with two electrodes: collector and emitter. N-drift, P-base, and N+ collector regions are grown using MOCVD technique. Shallow low-energy Si-ion implanted N+ regions make the contacts between the emitter electrode and the semiconductor. Optical window is defined by the Si3N4 anti-reflecting layer of a particular thickness, which results in minimum reflection of light. In the blocking state, the applied voltage is supported by the reverse biased P-N junction between the P-base and N-drift regions.

![Image](image-url)

Fig. 1: (a) Device structure of the OTPT. (b) Micrograph of a prototype OTPT and its die wire bonding. (c) Packaged realization of the OTPT [1].

In Fig. 2, 3-D diagrams of electric-field distribution and photogeneration rate across the device in Fig. 1a is shown. This rectangular electric field enables reduced effective distance between collector and emitter electrodes of the unit cell of the OTPT and yields higher optical gain, because photogenerated carriers travel less distance inside N-drift region. Also, a rectangular electric field (Fig. 2a) mobilizes the photogenerated carriers in a uniform manner, as demonstrated in Fig. 2b. Moreover, the quantum efficiency and the switching speed of the OTPT depend strongly on the minority-carrier recombination lifetime in the P-body region. A higher doping of the P-body results in a shorter lifetime, which ensures faster turn-off due to rapid recombination when the light shuts off, but, it also leads to a lower device gain because photogenerated carriers recombine easily and have less chance of contributing towards conductivity modulation.

Snapshots of the turn-on and turn-off dynamics of the OTPT are shown in Fig. 4. Turn-on and turn-off delays are measured as the difference between the time instants of the initiation of the laser-drive signal and initiation of the change in the OTPT voltage. Rise and fall times are defined as the time taken to change the OTPT voltage from 10% to 90% (or vice versa) of its steady-state value.

Fig. 4: A snapshot of the (a) turn-on delay, (b) turn-off delay, (c) rise time and (d) fall time of the OTPT under the following conditions: \( V_{bias} = 60 \text{ V}, R_{load} = 1000 \Omega \), frequency \( = 50 \text{ kHz} \), duty cycle \( = 50\% \), and optical power \( = 0.5 \text{ W} \). Scale for the vertical axis is 10 V/div while for the horizontal axes are: (a) 40 ns/div, (b) 100 ns/div, (c) 40 ns/div, and (d) 200 ns/div, respectively. For (a) and (b), the top trace is the voltage across the OTPT and the bottom trace is the output current signal of the laser driver. The laser-driver current signal is measured through an internal current monitor of the laser-driver and is of negative polarity.

The threshold current, at which the lasing starts, is \( \approx 6 \text{ A} \). [1]

Subsequently, attempt was made to integrate the OTPT as a driver for a set of higher-voltage power semiconductor devices to realize optically-triggered hybrid power devices. In Fig. 5, the schematic diagram of one such hybrid package and the tested prototype package is shown. The aim of such hybrid packaging is to reduce the interconnect length to minimize the parasitic impedance between the OTPT(s) and the PSD due to interconnects.

Fig. 5: Hybrid packaging scheme with two OTPTs coupled to a vertical PSD die. Corresponding prototype package is shown where the PSD die is SiC-based MOSFET. Electrical terminals are indicated by the symbols G, D, S, C, and E that represent gate, drain, source, collector, and emitter, respectively [1].