An Overview of Photonic Power Electronic Devices

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***Abstract*—This paper provides an outline on optically switched power electronic devices—an area of increasing promise. Starting with an outline of the need and benefits of optically activated power electronics, a brief chronological overview of the past optical-technology work is provided, followed by some of the recent novel work conducted by the author's group. The latter focuses on optical power semiconductor device technologies at different voltage levels and relatively recent device controls technologies. Finally, looking forward, some of the potential application areas of photonic power electronics are captured.**

***Index Terms*—Control, devices, electronics, optical photonic, power, SiC. GaN.**

I. Introduction

SEMICONDUCTOR electronic devices operate by the controlled motion of charge carriers inside them. One has to induce some nonequilibrium in the charge carrier density to operate a semiconductor device [1]. This can be achieved by electrical injection, or by optical injection, or by thermionic emission [2]. Optically activated devices fall within a special class of electronic devices where the transport or the initiation of transport of these charge carriers is done by photonic energy.

Optically activated devices operate on the principle of photogeneration [3]. The phenomenon is illustrated in Fig. 1, where an electron is transported from the valence to the conduction band by the incidence of a photon. The photon energy (hν), where ν is the frequency of the light and h is the Planck's constant, must be greater than the bandgap energy (E_g) of the semiconductor, for photogeneration to occur. Transport of one electron from valence band to conduction band also implies the generation of a hole in the valence band. So, optically excited generation occurs in electron–hole pairs. These electron–hole pairs generated by light incidence take part in current conduction in the device.

Advancement in power electronics has always been dependent upon the advances in power semiconductor switches. Starting from the early days of Si-based p-n junction rectifier and power bipolar junction transistors (BJTs), and cruising through thyristor, gate turn-off thyristor (GTO), power MOSFET, insulated-gate bipolar transistor (IGBT), integrated gate-commutated thyristor (IGCT), static induction transistor (SIT), we have now reached the age of advanced devices like superjunction MOSFETs, SiC-based Schottky diodes, SiC MOSFETs, SiC IGBTs, GaN-based HEMTs/HFETs [1], [4]–[7]. Most of them are electrically operated, i.e., the control signal to open or close the switch in such a power electronics system is electrical. This can, for instance, be either the base drive current for a power BJT or the gate-drive voltage for a power MOSFET or an IGBT.

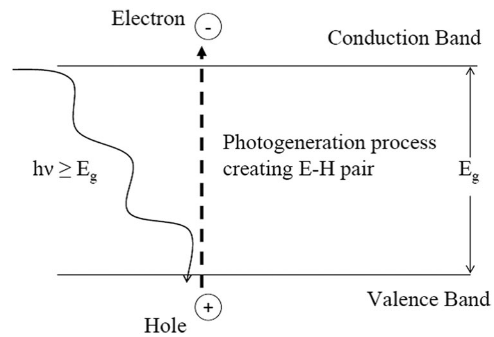

Fig. 1. Optical activation process by the incidence of an optical pulse having energy (hν) greater than the bandgap energy (E_g) of the semiconductor and the corresponding creation of the electron–hole (E-H) pair [2].

Optically activated devices, when used in power electronics systems, have the potential to significantly increase the switching frequencies for all power levels and eliminate some of the major problems of electrically triggered devices. In an electrically activated device, the gate of the power device is fired electrically; while the triggering action in an optically activated device is provided by the photogeneration of electron–hole pairs, which may be direct band-to-band transition or between the band and the deep levels in the energy gap depending directly upon the energy of the photonic source [3]. Because of this unique characteristic, optically activated devices provide jitter-free operations, fast opening and closing times, high repetition rates, and fast recovery times, all of which enable high frequency of operation. In addition, optically activated devices are scalable for handling low, medium, and high power and several have low storage effects and inductance, which can be useful for monolithic integration.

With regard to optical control of power semiconductor devices, it is an important technical approach for addressing fundamental limits associated with limitations imposed by multidimensional field distributions and limitations imposed by multidimensional charge transport. The optical injection of either minority or majority carriers over large areas is straightforward. For instance, a device base or gate region can be irradiated with photons possessing at least the bandgap energy to inject electron–hole pairs in thin regions where charge injection initiates conduction. Absorption of photons with sub-bandgap energy makes it possible to optically inject carriers into large volumes, such as the drift region, as well. Both processes fundamentally eliminate the delay and the nonuniform current

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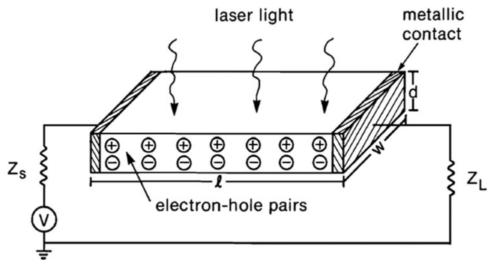


Fig. 2. Illustration of a PCS [8].

density distributions associated with the electrical transport of charge carriers to the gate or base control regions of large power devices. However, there is another reason to consider optically activated power switches. The optical stimulation of deep trap levels can also remove mobile charge from the conduction and valence bands, thus providing a method for optically controlling a power semiconductor switch both ON and OFF.

On a circuit level, the simple difference between optically and electrically activated systems results in some key additional advantages for the former. First, in an optically activated device, there is complete electrical isolation between the gate driver and the power stage. As such, very high di/dt and dv/dt, which may cause significant reliability problems in electrically activated devices at high switch frequencies, have limited impact on an optically activated devices. Therefore, the basic architecture of the gate driver in an optically activated device is simple. Second, for two- and higher level electrically triggered switching converters, different designs of low- and high-side drivers are required; the latter is especially challenging to design for medium and high-power applications.

For an optically activated converter, the designs of high- and low-side drivers remain the same. Third for firing optically activated devices, optically multiplexed triggering signals (as often encountered in modern optical-fiber based control systems) do not need to be converted back to electrical signals. This leads to simplicity of overall design, enhanced controlled bandwidth, enhanced reliability of the system, and monolithic integration. Fourth, as the switching frequency of an electrically activated device increases, parasitic oscillations may be induced in the driver circuit owing to coupling effects between the device capacitance and the parasitic inductance of the gate connection and also due to transmission-line effects. This may lead to failure of the gate driver; with an optically activated device such possibilities do not arise. Clearly, optically activated devices have the potential to address these problems encountered in conventional electrically activated devices. They are emerging devices for power electronics applications and much research is ongoing as well as needed on in this area.

While Section I provides the introduction to the photonic devices for power electronics, Section II provides an overview on the past work in this area. Sections III provides an outline on recent and ongoing work primarily at author's group as outlined in the abstract. The distinction between the past and recent work is simply that while the former work has concluded, the latter continues to be the basis for some of the ongoing work. Section IV provides an overview of work that is going to be and/or

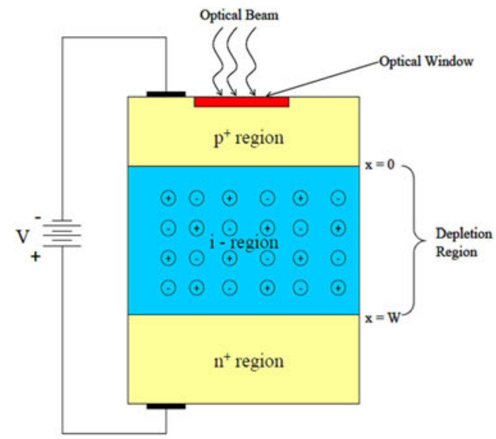


Fig. 3. Schematic of a photodiode.

can be potentially realized further extending the promise of applications of photonic devices for power electronics. Finally, in Section V, a qualitative assessment of the broad category of optically switched devices outlined in this manuscript has been provided from the standpoint of their applicability for power electronics.

II. Past Work

One of the main uses of optical activation and control could be enabling a different scaling law for the design of high blocking-voltage power devices. The depletion region charge distribution fundamentally limits the blocking voltage in conventional devices. Even then the fundamental limit is seldom achieved because surfaces and curvature in the doped regions produce electric field magnitudes in excess of the critical value at reduced voltage.

A conceptually different approach uses a neutral semiconductor with very low equilibrium conductivity between two ohmic contacts to block larger voltages. This approach, the heart of the photoconductive switch (PCS) [8] and as illustrated in Fig. 2, typically uses a semiinsulating (SI) semiconductor. There are two operating modes of PCS that have been researched rather extensively. The first is the optically activated PCS (with photoconductive gain greater than one) and the second is the optically sustained PCS (with photoconductive gain less than one).

There are advantages and disadvantages of the optically activated PCS in power electronics. One advantage is the voltage scalability of the PCS by increasing the linear dimension. Thus, a single PCS can be made to handle much larger voltages than a typical conventional power switch (e.g., thyristor or IGBT). Another advantage is that the regenerative conduction mechanism is not easily triggered by electrical means, making an optically activated PCS virtually immune to spurious dv/dt triggering in the conventional power electronics applications. Indeed, the dielectric strength of the PCS usually increases under transient voltages (i.e., with increasing dv/dt) [9]. The combination of fewer switches and optical triggering can simplify the design of a multivalve converter.

The main disadvantage with the conventional PCS design is that it is difficult to design the switch for a useful blocking

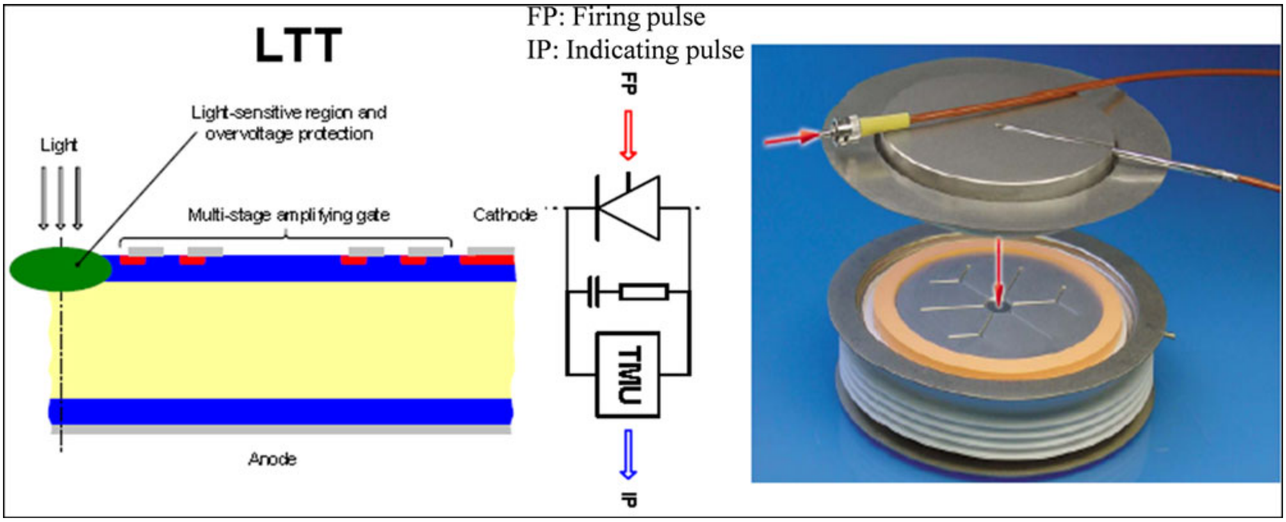


Fig. 4. Si-based LTT [13].

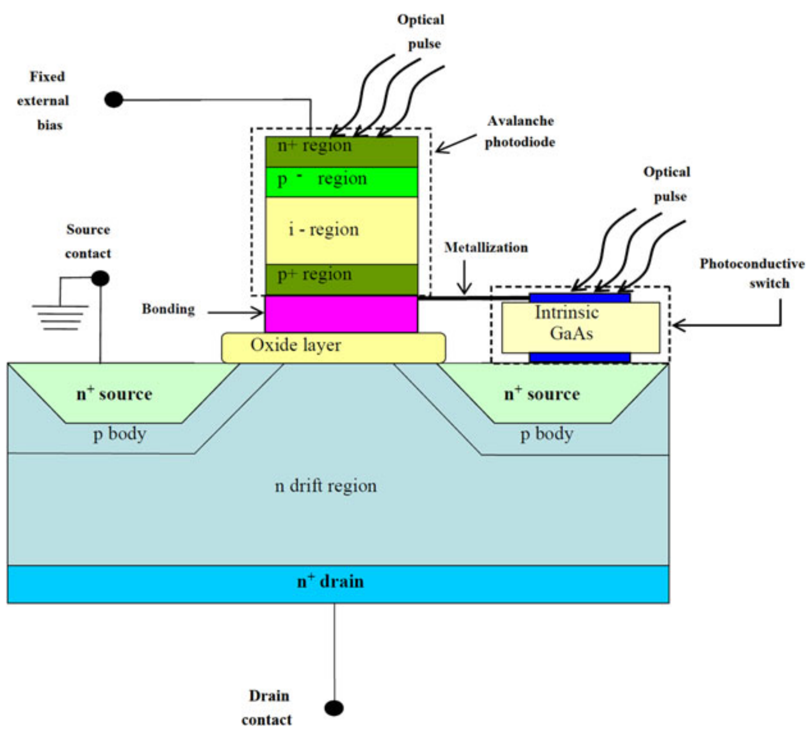


Fig. 5. OT-MOS structure.

voltage and an acceptable conduction loss while achieving an acceptable average power from the activating optical source. Consequently, there are no widely accepted, commercially available PCS for power electronics applications. For power electronics applications, the laser energy required to sustain conduction is prohibitive. These PCS devices appear limited to highly specialized pulsed-power applications.

There is another attractive physical mechanism available in optically activated power switches via optical stimulation of deep trap levels yielding a mechanism for optically controlling the conduction state of power semiconductor switches both ON and OFF. The observation of infrared quenching of photoconductivity in copper-doped GaAs was reported in [10]. Infrared quenching in copper-doped semiinsulating GaAs has been applied to the PCS concept to produce the bistable opticallystimulated switch (BOSS) [11].

The BOSS, fabricated as a conventional PCS, shares the advantages and disadvantages of the optically activated (closing) PCS described previously without suffering, to the same degree, the inefficiency of the optically sustained (naturally opening) PCS. However, the need for sources with two separate laser wavelengths increases complexity and cost, and the problem of designing an efficient cost-effective PCS for power electronics applications remains. One solution could be to include the optically active material that forms BOSS in the control region of a conventional power semiconductor switch, such as the base

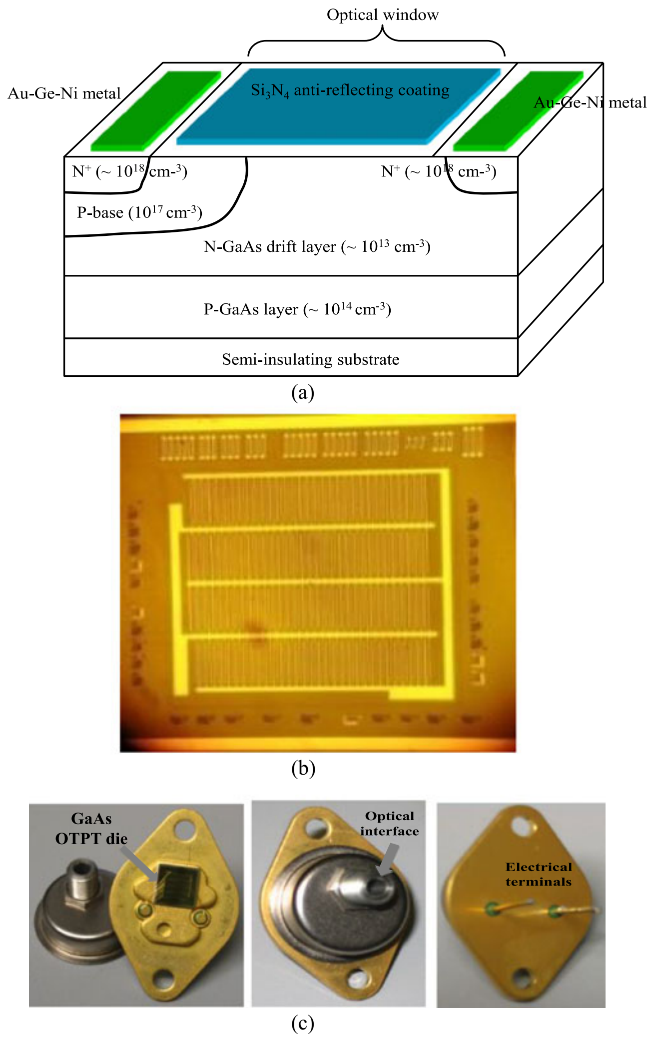


Fig. 6. (a) Device structure of the lateral OTPT; (b) Micrograph of the OTPT; and (c) Packaged realization of the OTPT.

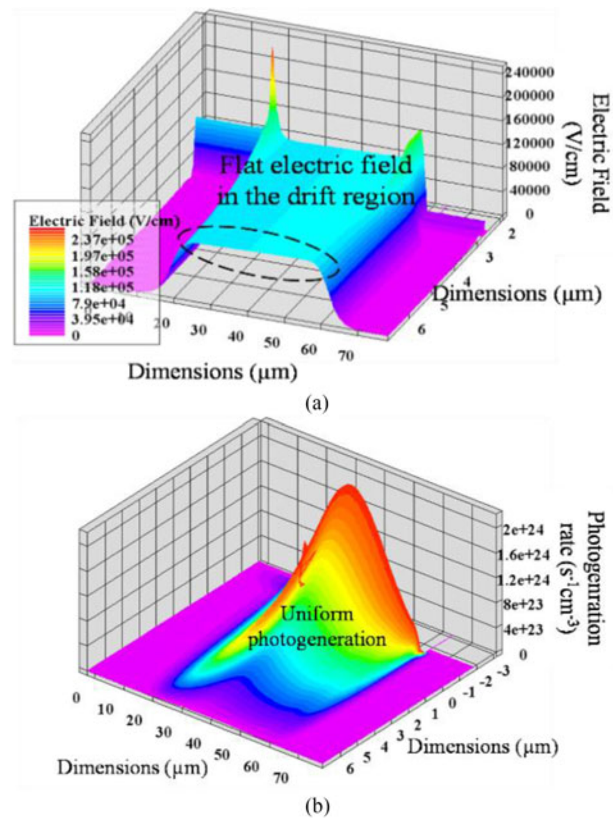


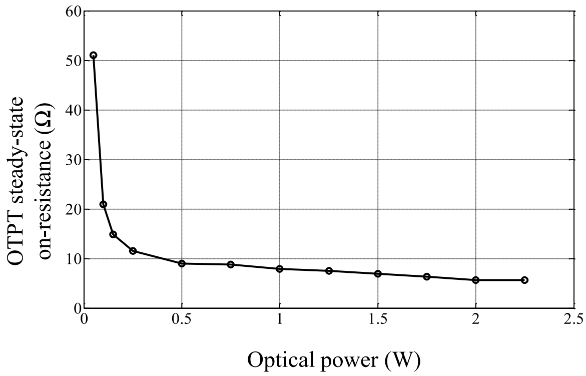
Fig. 7. (a) Three-dimensional view of the electric-field distribution inside the OTPT at the instant of breakdown. (b) Three-dimensional view of the uniform photogeneration rate inside the OTPT.

of an optically activated BJT or the channel of an optically activated MOSFET.

One way to preclude the need for two light sources in BOSS without compromising the repetition rate while ensuring high gain (and hence, lower beam intensity) is using optically activated lateral and vertical p-i-n diodes, a few of which have been reported in [12] and [13]. Most of these devices are targeted for low-frequency but high-power applications (e.g., pulsed-power switching or microwave power generation). Fig. 3 illustrates a simple p-i-n diode schematic with the incident optical beam and the photogeneration in the intrinsic region. Normally, the diode is reverse biased and conducts very small dark current in its off-state. When the light falls on it through an optical window, excess carriers are generated due to high electric field and the conductivity increases manyfold and the diode conducts current. However, high electric field in such devices often yields long-term reliability issues.

A bipolar optical device that overcomes the limitation of reverse-bias optical diode while ensuring voltage stability even at high voltages is the light-triggered thyristor (LTT) [14], [15]. A typical light triggering of thyristor is achieved by localized illumination at a centered site of the device. There is an optical well and surrounding it there lay a pilot thyristor and an amplifying thyristor structure. Photogenerated electron–hole pairs cause a lateral current flow from the center of the well, driven by the anode bias. This lateral current induces a voltage drop in the main cathode junction, which is sufficient to turn ON the pilot thyristor. The pilot thyristor then turns ON the larger amplifying thyristor. This, in turn, is able to drive the gate arms of the main device. The well is very sensitive and normally few microjoule of optical energy is sufficient for taking the device into full conduction from a reverse blocking state. Sometimes, there can be more than one amplifying gates depending upon the current requirement of the device. Fig. 4 shows a schematic of an LTT based on Si material base. An LTT could be an elegant device for many applications, especially at high power. It can yield high reliability and compact system design. Further, optical activation leads to enhanced immunity to electromagnetic noise and isolation between control and power stages. However, Si-based LTTs are not suitable for fast switching at high voltage.

Unlike the LTT, conventional optothyristors are normally made of III–V compounds such as GaAs, AlGaAs, and InP. Direct-bandgap nature of these materials allows optical efficiency and switching speed to be higher and also facilitates



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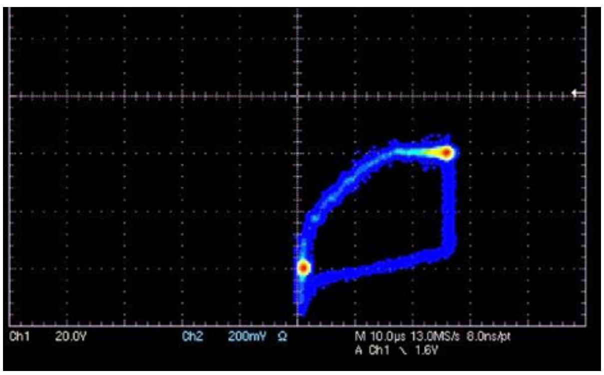
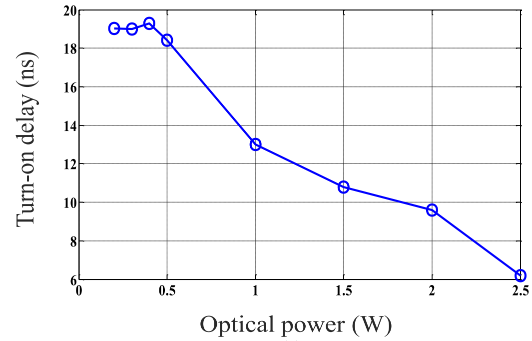


(b)

Fig. 8. (a) Experimental OTPT on-resistance with varying optical power under the following conditions: $V_{\mathrm{Bias}} = 10$ V, $R_{\mathrm{load}} = 50\ \Omega$, frequency = 5 kHz, and duty cycle = 50%. (b) *X–Y* phase plot of the OTPT voltage with optical signal illustrating the nonlinear variation of conductivity with optical power variation.



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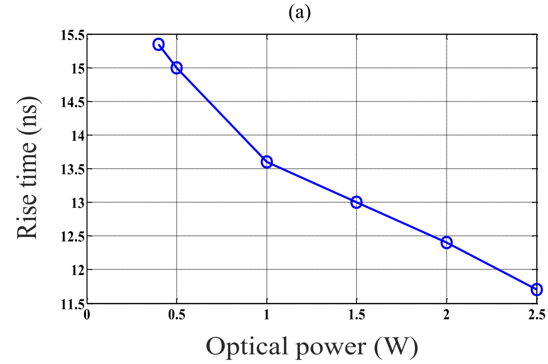

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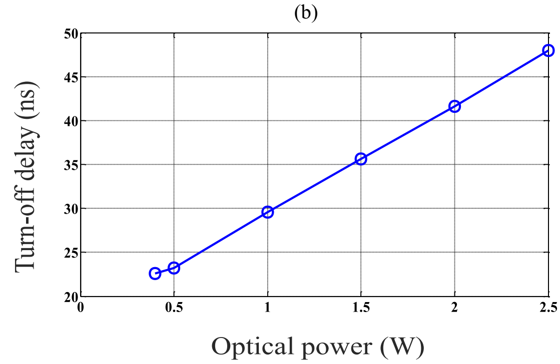

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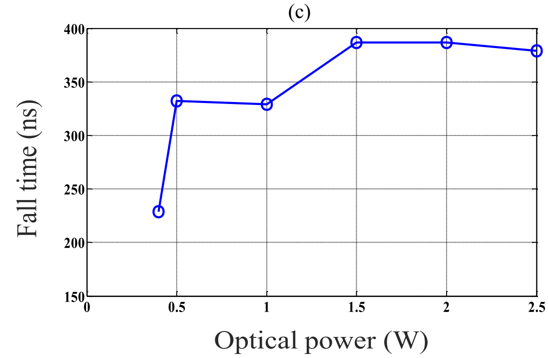


(d)

Fig. 9. Experimental switching dynamics of the OTPT under the following conditions: $V_{\mathrm{Bias}} = 60$ V, $R_{\mathrm{load}} = 1000\ \Omega$, frequency = 50 kHz, and duty cycle = 50%.

heterostructures to be explored [16]. Although successful fabrication and application of optothyristors have been demonstrated for high-voltage pulsed-power systems [16], [17], surface degradation, edge breakdown, and deep-level effects of the semiinsulating base layer can lead to early breakdown at a voltage much less than the theoretical value. As such, careful design optimization is a necessity. Another interesting approach has been reported in [18] to integrate the optical-control detection circuitry with power device and to create an LTT with an MOS amplifying gate structure.

Unlike the bipolar devices, among the power semiconductor devices, MOSFET is the most preferred choice for high-frequency applications due to its unipolar conduction, which does not introduce any minority carrier storage delay. However, optical switching of power MOSFETs has not been studied much. Optical control of the MOSFET or MIS structure, in general, has been reported in [19] and [20]. But, they are primarily in the domain low-power optical communication or sensor applications. Modulation techniques for an optically triggered power MOSFET (OT-MOS) has been reported in [21]. A vertical double-diffused MOS (DMOS) is controlled by a turn-on and a turn-off pulse and the hybrid device structure schematic, comprising a Si-based DMOS, a GaAs-based photodiode, and a GaAs-based PCS, is shown in Fig. 5. The photodiode acts as a photogenerated current source, which, upon shining the turn-on pulse on it, modulates the i-drift region resistance, conducts current (supplied by the reverse bias source) and charges the gate capacitance of the DMOS above the threshold voltage to turn the OT-MOS ON. Again, during turn-off, another optical pulse falls on the PCS to modulate its conductivity, provides a short-circuit path through the PCS, and discharge the gate capacitance of the DMOS to turn it OFF. So, the turn-on and turn-off time can be

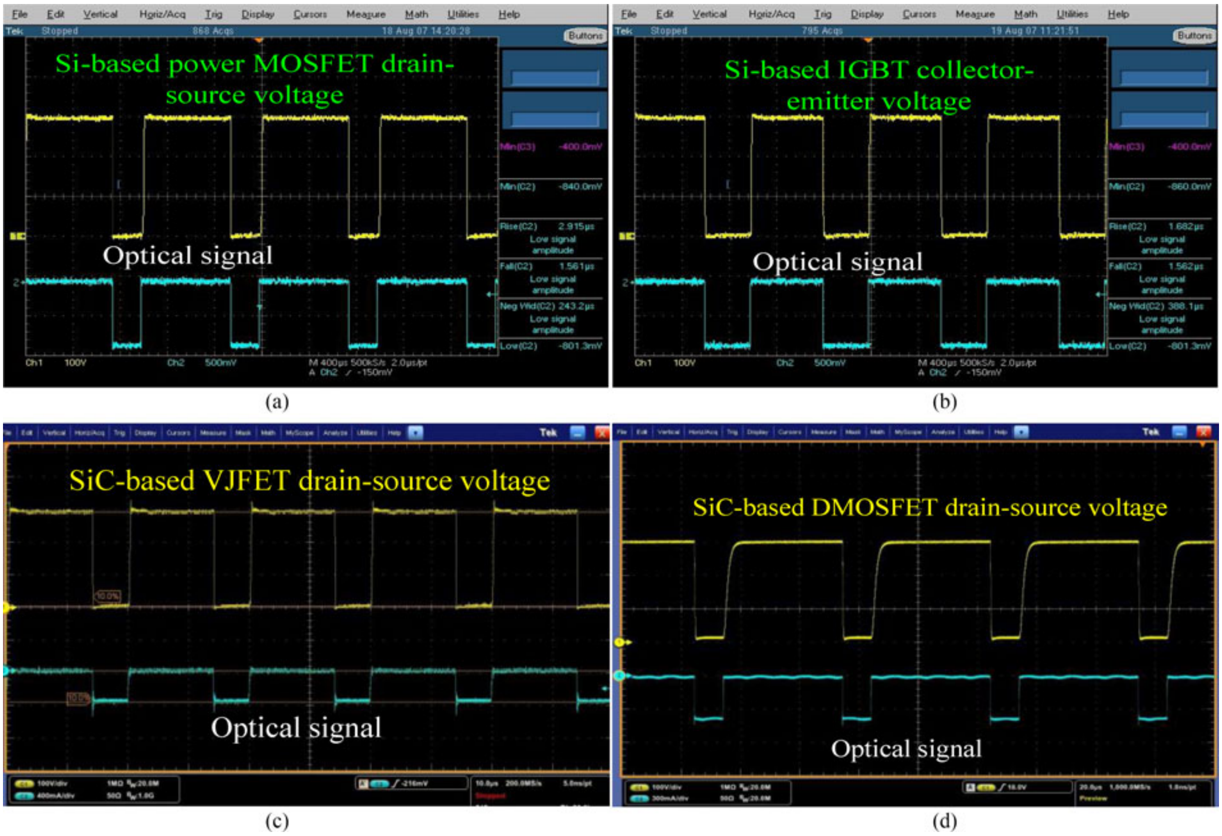


Fig. 10. OTPT-based switching of (a) Si-based power MOSFET, (b) Si-based IGBT, (c) SiC-based VJFET, and (d) SiC-based MOSFET. The dynamics of the SiC MOSFET is comparatively slower due to the high input capacitance of the device and is not attributed to the OTPT.

adjusted either by manipulating the amplitudes of the photogenerated current-source strength and PCS conductivity or by varying the time period of the triggering pulses, thus allowing the gate capacitance of the OT-MOS to charge or discharge for a varying time. Consequently, there are possibilities of using both amplitude- and pulsewidth modulation techniques for the activating optical pulses [22], [23].

In line with above optically activated field-effect devices, an approach to activate an IGBT with a direct optical pulse, incident in its channel region has been reported in [24]. It shows improvement in the on-state voltage drop of the optically activated IGBT given that the channel width in this case depends upon the absorption depth for the particular semiconductor material-optical wavelength pair and it can be significantly higher than the intrinsic Debye length (a few nanometer), which is the default channel width for an MOSFET. However, Liao *et al.* [24] treated only the improved current density and voltage drop and does not report switching results for the optically activated IGBT. Yet another photonic field-effect device is the optically activated MESFET [25]. When the device is illuminated with light, with photon energy greater than the bandgap energy, illuminated channel region contributes optically activated gate photocurrent. Illuminated interelectrode epilayer photocurrent modulates the conductivity of the epilayer. Also in the episubstrate barrier region excess photogenerated carriers reduce the barrier height and the illuminated part of the substrate contributes to the substrate current. Finally, in [26], another field-effect device—optically modulated series-coupled SIT—is outlined. In it, the ground-referenced low-power optical trigger sources are isolated from the high-voltage switch assembly through optical fibers, and this results in reliable, jitter-free operation [26]. Optically activated SITs are also made from III–V materials to leverage the advantage of high critical electric field and higher carrier mobility of these elements.

III. Recent and Ongoing Work

Fig. 6 shows the device structure of a GaAs-based optically triggered power transistor (OTPT), micrograph of a prototype OTPT, and its packaged realization [27]. GaAs has a high level of light absorption, and hence, a high quantum efficiency. Further, the rectangular electric field enabled by the RESURF structure enables reduced effective distance between collector and emitter electrodes of the OTPT and yields higher optical gain. Also, a rectangular electric field [see Fig. 7(a)] mobilizes the photogenerated carriers in a uniform manner, as demonstrated in Fig. 7(b). The quantum efficiency and the switching speed of the OTPT depend strongly on the minority-carrier recombination lifetime in the p-body region. The on-state resistance of the OTPT varies with the optical intensity as shown in Fig. 8(a), while Fig. 8(b) demonstrates the nonlinear variation of conductivity with optical power variation for the OTPT. Snapshots of the turn-on and turn-off dynamics of the OTPT are shown in Fig. 9.

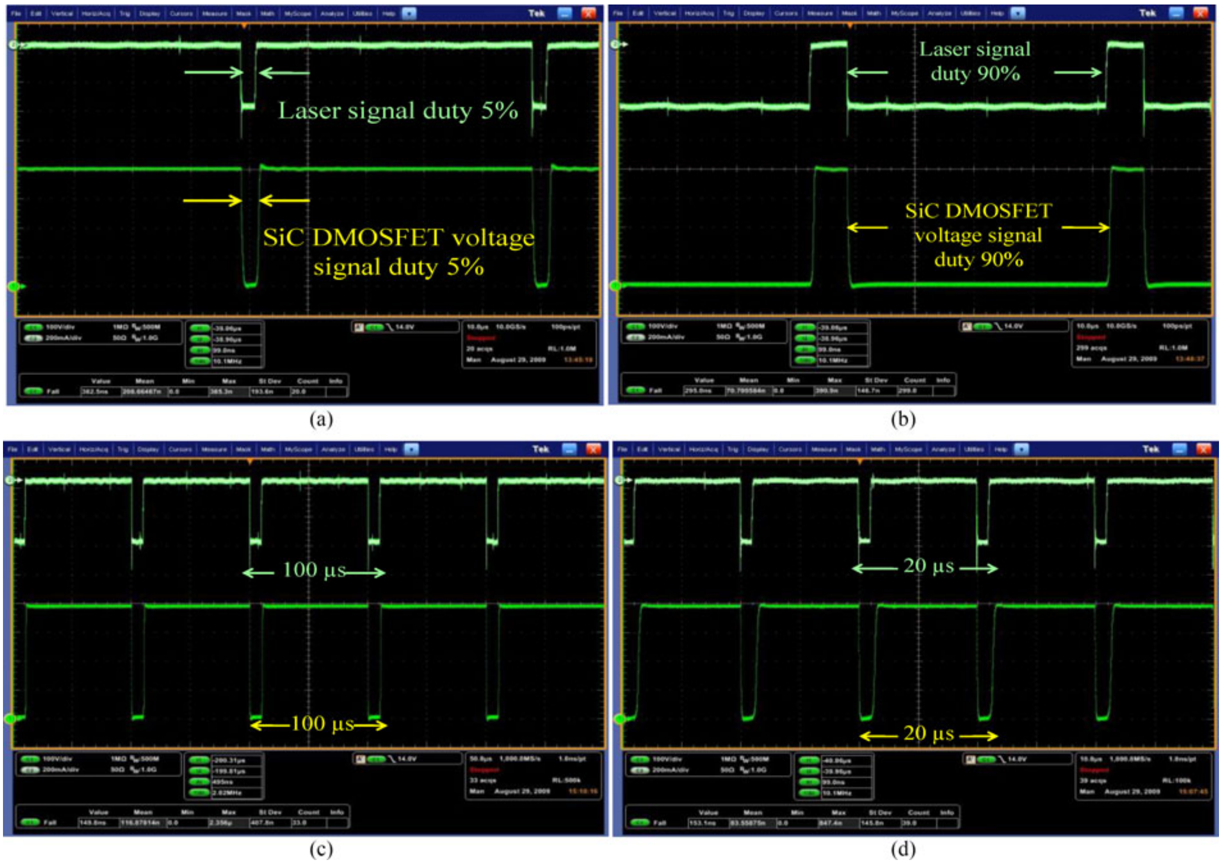


Fig. 11. (a), (b) Switching waveforms at 400-V bias, 20 kHz, and at 200 °C case temperature with duty cycles of (a) 5% and (b) 90%. (c) and (d) Switching waveforms at 400-V bias, 10% duty cycle, and at 200 °C case temperature with frequencies of (c) 10 kHz and (d) 50 kHz.

Subsequent to the evaluation of the OTPT, the concept of optically activated hybrid power semiconductor device was tried using a combination of triggering OTPT(s) and high-voltage devices such as SiC MOSFET, SiC VJFET, Si IGBT, and Si MOSFET devices. Fig. 10 [27] shows the transient performance of such optical hybrid devices. Such integrated hybrid device work has been carried further for high temperature operation. For instance, Fig. 11 shows the transient operation of an OTPT-based SiC MOSFET at 200 °C under varying pulse width and duty cycle for frequencies ranging from 10 to 50 kHz. This demonstrates the photonic control of SiC MOSFET at high temperature over a range of switching conditions. It is worthwhile noting here that if very-high-speed switching dynamics is not a necessity, then a higher gain multistage OTPT can be used to significantly reduce the optical power requirement while accepting a slightly slower switching speed. Fig. 12 illustrates this point using an MOSFET being driven by a two-stage OTPT driver.

More recently, a vertical OTPT based on Si has been designed, fabricated, and characterized that can support much higher current of operation and fast switching dynamics [28]. The device is designed to support a junction temperature of 200 °C. Even though the initial goal of the OTPT is to support an optically triggered emitter turn-off thyristor, the vertical OTPT can be used independently and for other hybrid configurations. Figs. 13 and 14 demonstrate the information regarding the OTPT.

An applicability of the OTPT has been captured via a recent patent [29] that outlines a single-biased all-optical emitter-turn-off (ETO) thyristor. Fig. 15(a) outlines the structure of the device. The initial results based on different embodiments of OTPTs have been reported in [28], [30], and [31] and are encouraging. One such result at high current is shown in Fig. 15(b). There are basic solutions to mitigate the undesired turn-on of the gate (which is an issue for the conventional self-gated electrically activated ETO as well) including 1) reducing packaging parasitic inductance, 2) choosing n-MOSFET with higher threshold voltage, 3) a standard solution of placing a Zener diode in the gate-to-drain path of the n-MOSFET, and 4) adding another p-MOSFET in series with the n-MOSFET. Solution 4 mitigates the gate current during turn-on but leads to an additional p-MOSFET die of the same current rating as the n-MOSFET. The solution c leads to an additional Zener diode but its current rating is less compared to the p-MOSFET since it is placed in the path of the gate of the n-MOSFET. Solution 2 is coupled to the di/dt, thyristor forward drop, and packaging inductance. Notwithstanding the approaches outlined in b through d, reduced packaging inductance has an overall benefit, especially at very high di/dt. If successfully realized, the all-optical single-bias ETO structure in Fig. 15(a), has key advantages over electrically activated ETO [32], MTO, and IGCT. Work is ongoing in this regard.

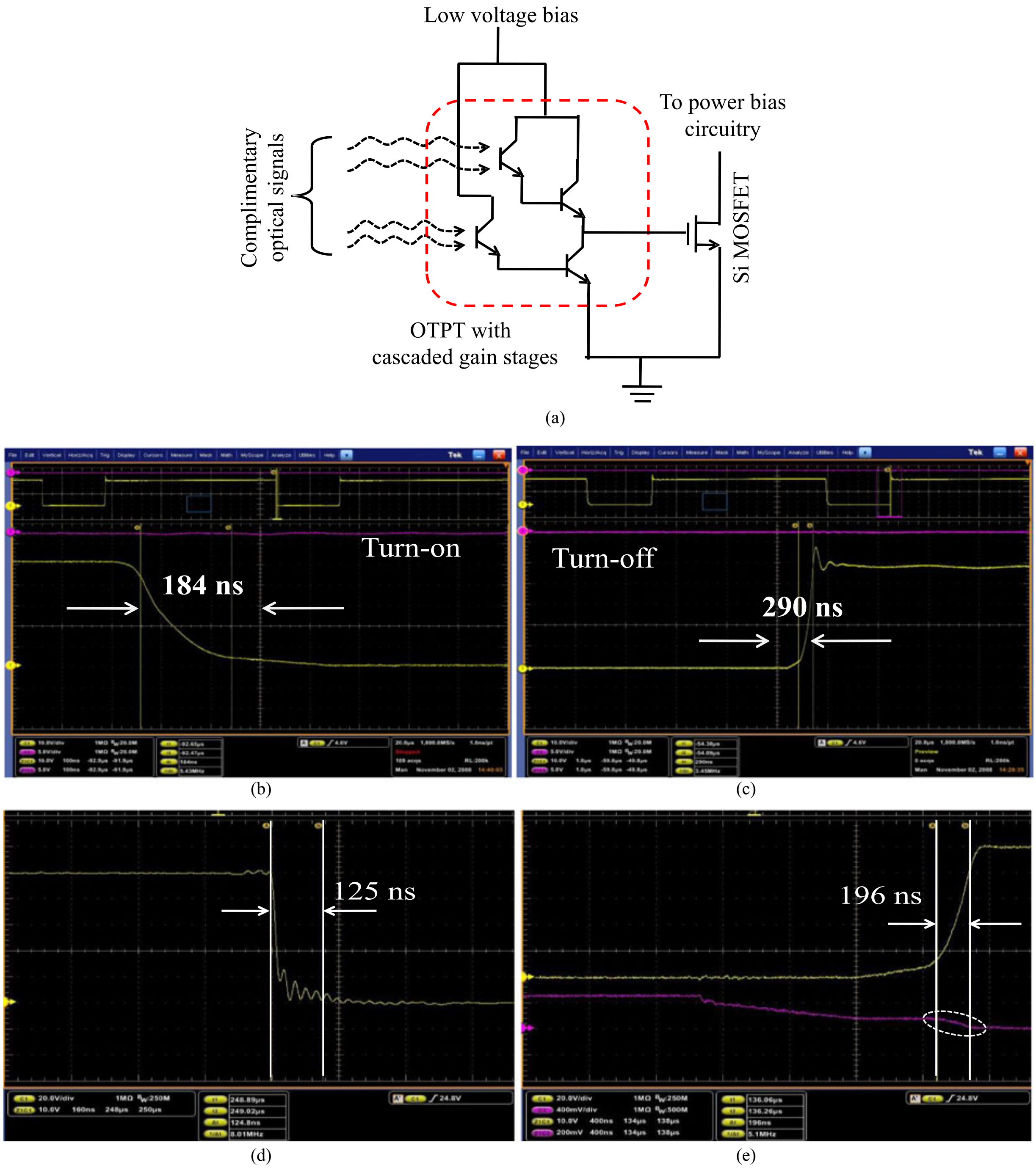


Fig. 12. (a) Two-stage higher gain OTPT-based driver triggering a Si MOSFET. (b) and (c) Rise and fall times of (a) with 50-mW optical power. (d) and (e) Corresponding rise and fall times of a single-stage OTPT-based driver triggering Si MOSFET.

Apart from synthesis of optically activated power semiconductor devices that meet emerging performance needs, there is a need to control the light-delivery mechanism to switch the optical device appropriately. Initial work in this regard using OTPT-based control has been outlined in [33], which outlines the need for switching-transition control outlined in [34]. For instance, Fig. 16 shows how the increment in the OTPT optical intensity leads to reduction in the Miller-plateau width of a Si CoolMOS. Subsequent work has advanced these initial works with additional technological capabilities as captured in [35] and [36]. Fig. 17 demonstrates one such experimental controller for the optical device developed recently [36].

IV. Future Work and Potential Opportunities

Looking at the historical work and observing the areas of applications where electrical activation of power semiconductor devices have had reliability issues, there are several areas of applications where optically activated power electronics and switched-power-system technology is applicable and beneficial.

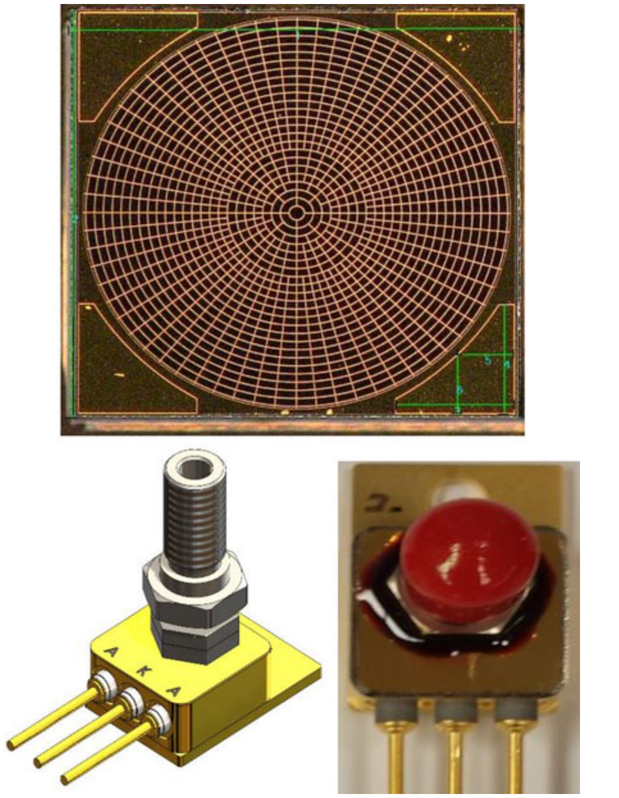


Fig. 13. Vertical experimental OTPT device geometry, packaging architecture, and actual package.

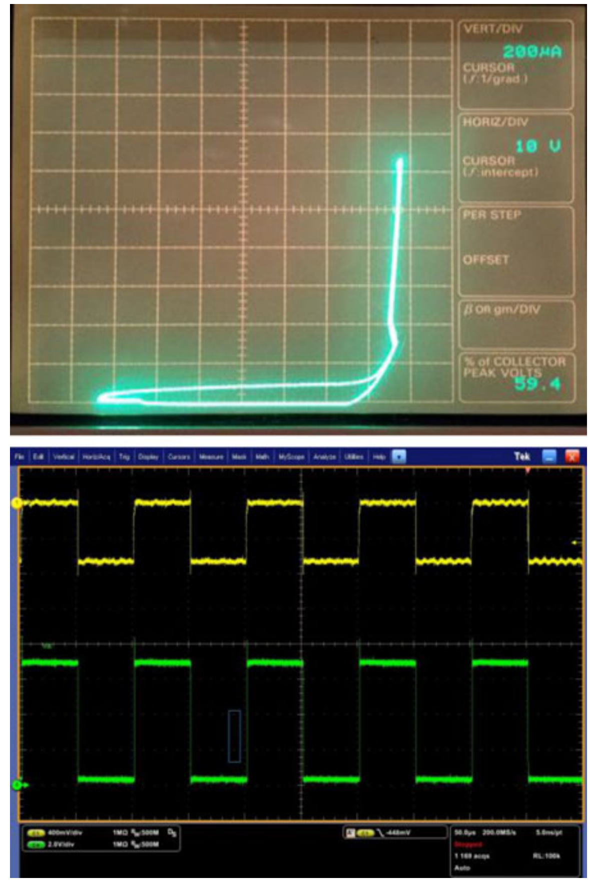
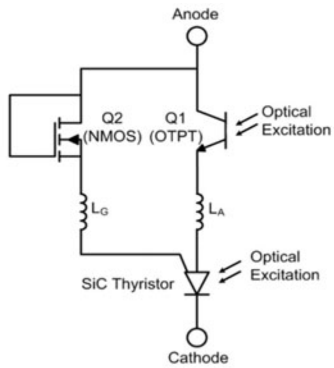


Fig. 14. Experimental I–V and switching characterizations of the vertical OTPT outlined in Fig. 13.

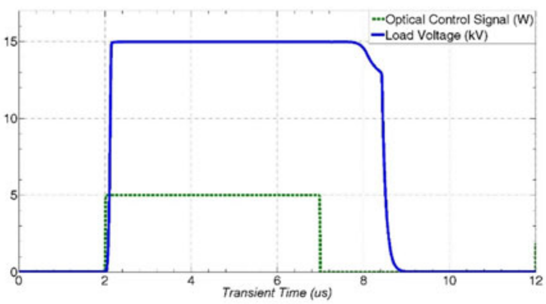
One core commonality in some of these applications appears to be the high d*v*/d*t* and d*i*/d*t*, which transcends very high voltage and moderate frequency as well as low voltage and very high frequency (VHF). For instance, for next-generation optical semiconductor-device-based high-voltage solid-state electronic control and power-quality applications at transmission and distribution levels, photonic power electronics technology (e.g., [29], [37], [38], and others) provides advantages with regard to enhanced reliability, seamless scalability, efficient operability, and dynamic controllability. Needless to say, some of the advantages carry over to other legacy as well as emerging applications (e.g., transfer and grid-isolation switches of a microgrid, high-voltage and high-power motor drive and power-quality-related conditioners, medium-voltage electric-traction locomotive) but need to be evaluated on a case by case basis.

Yet another set of high-power application encompasses pulsed-power systems [39]–[41] and rapid fault isolation. These applications, unlike typical power electronic applications, typically require rapid burst of energy in a short duration of time with minimal switching-initiation delay under conditions of relatively slow repeatability. Fig. 18 illustrates a GaN-based optical pulsed-power switch [42] that is rapidly activated optically with a rise time of about 10 ns. The activation is achieved at high gain using a monolithically integrated MISFET that provides a transient high electric field just before the device is activated.

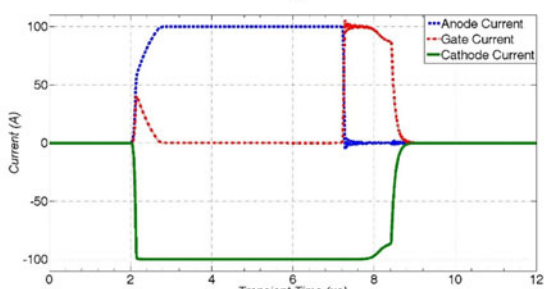
During the near-singularity event that leads to high d*i*/d*t*, optical technology provides enhanced immunity to electromagnetic noise (as illustrated in Fig. 19 [43]) and the direct-photogeneration capability reduces switching-onset delay. Several of the advantages of high-voltage and high-current photonic power electronics and switched-power-systems technologies remain even at lower voltages with progressively enhanced tangible benefits at VHF and ultrahigh frequency of operation. Areas of such applications can be power amplifiers for wireless communication and power amplifiers for radars. Another set of application encompasses system technologies such as fly-by-light for aerospace and avionics [43] or electric-vehicle applications with coexistence of electrical-power and electronic-communication systems. Yet another application encompasses dealing with electrical and electronic systems with plurality of floating grounds. Finally, and on a more recent note, the ability of power electronic system to support normal as well as fault modes of operation is being sought. A key to that resides with the power semiconductor device. Fig. 20 shows an early conceptual result in that regard. It illustrates how an OTPT-based optically controlled SiC MOSFET's on-state drop can be relatively easily controlled simply by adjusting the optical intensity of the OTPT. Thus, under normal operation, the optical intensity is so controlled such that the MOSFET drop is nominal (which is small), but at the onset of the fault, the intensity can be so controlled such that the MOSFET on-state drop is quickly increased thereby limiting the current.



(a)



(b)



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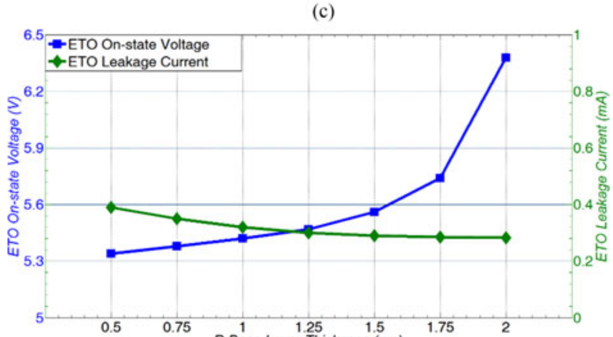


(d)

Fig. 15. (a) Structure of the single-bias all-optical ETO. L_G and L_A represent the packaged parasitic inductance. The high-voltage device is a SiC thyristor. (b)–(d) Initial results for the structure shown in (a) using a high-gain OTPT. (b) Voltage across the load and the optical control signal on the OTPT. (c) Output currents for the thyristor in the optically triggered ETO. (d) ETO on-state voltage and leakage current as controlled by the OTPT p-base thickness variation.

Overall, these outlined potential areas are by no means all encompassing. It is not unrealistic to surmise that additional areas of applications where photonic power electronics and switched-power-systems makes tangible impact are being pursued and/or being explored. Of course the viable realization of existing and emerging application will benefit significantly with continual

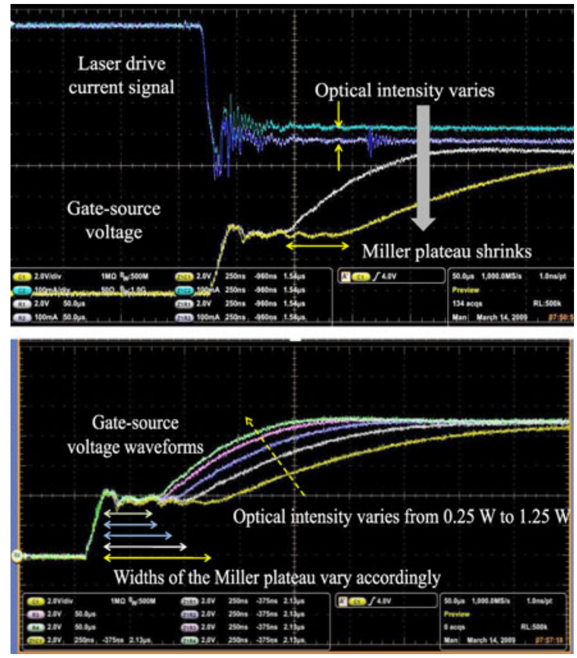
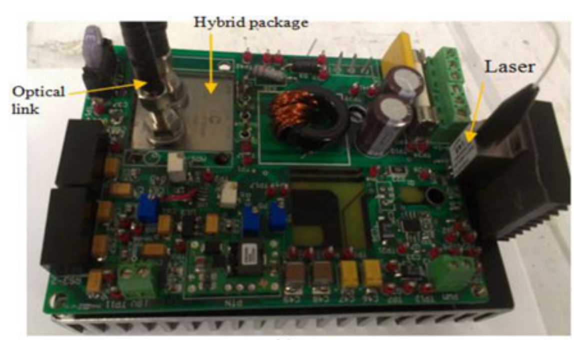
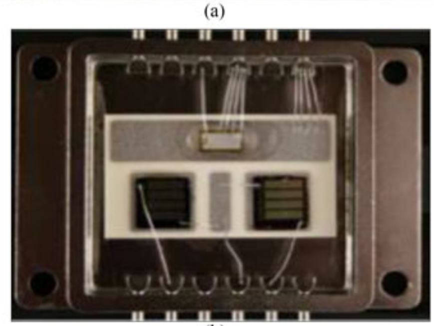


Fig. 16. Modulation of the Miller plateau of a Si CoolMOS (driven by OTPT) with varying optical intensity of the OTPT activation.



(a)


(b)

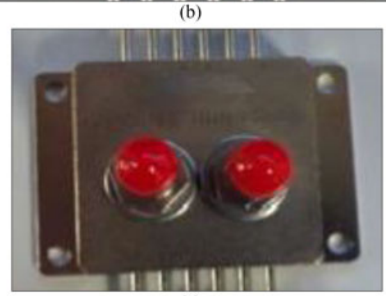

(c)

Fig. 17. (a) Experimental optical controller: fabricated board, which includes power circuit, control circuit, laser, and laser driver. (b) and (c) Packaged device used that uses the GaAs-based OTPT shown in Fig. 6(a).

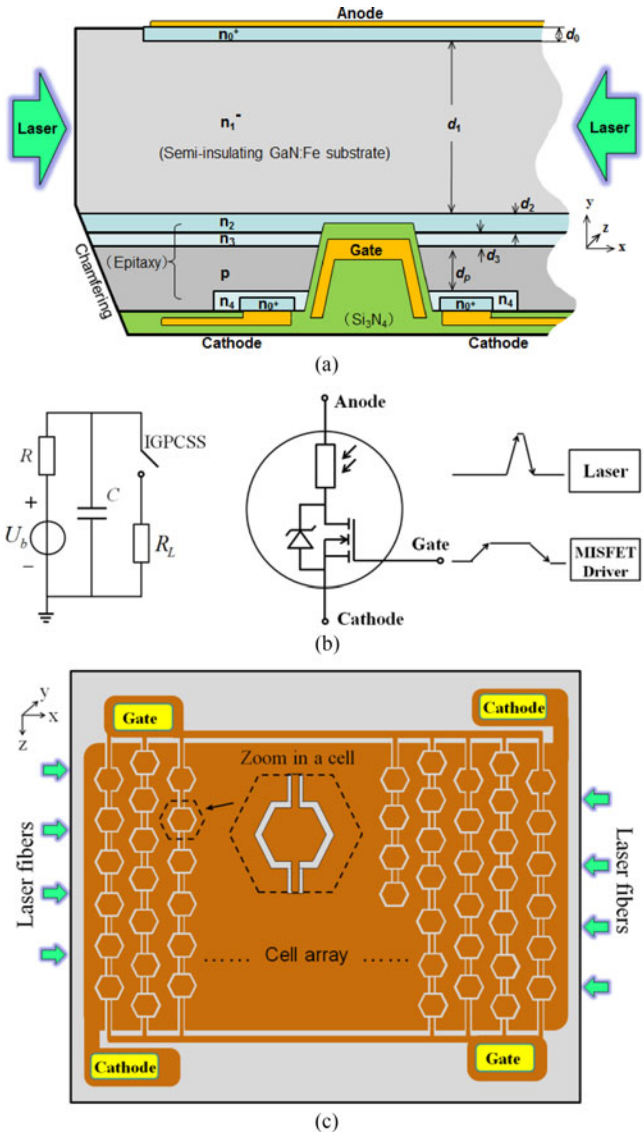


Fig. 18. (a) Lateral view of the GaN-based insulated-gate photoconductive semiconductor switch (IGPCSS). (b) Equivalent circuit model of the IGPCSS device (middle), illustrating the schematic diagrams of a bias source (left) and the timing sequence of trigger signals (right). (c) Bottom view of the GaN-based IGPCSS. The multicell-parallel insulted gates are arrayed with the shape of hexagonal honeycomb.

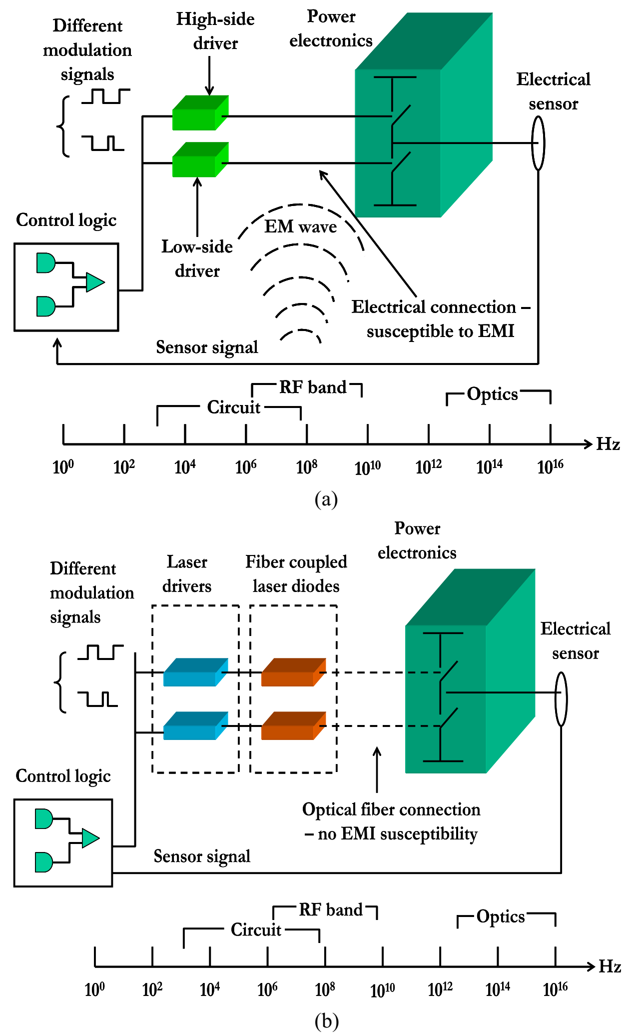


Fig. 19. Illustration of the difference in mechanism between (a) electrically activated and (b) optically activated power electronics technologies indicating the advantages associated with immunity from electromagnetic interference (EMI), electrical isolation between power and control stages, and reduced device triggering delay.

advancements in device realization and control implementation technologies. With regard to the former, new innovations in wide bandgap as well as narrow-bandgap device structures, materials, light-delivery mechanisms, and optoelectronic thermal packaging would of help. With regard to optical control, mechanisms of multiscale, dynamic, and reconfigurable switching-sequence-based and switching-transition controls [34], [44], [45] that exploit the unique and distinguishing properties of the optically activated and optically controlled devices needs to be explored and pursued.

V. Summary and Conclusion

In this paper, an overview has been provided on photonically switched devices with potential applications for power electronics. Initially, an overview has been provided on the suitability of optically switched device technologies for application space encompassing device and circuit and systems levels. At the device level, initially an outline on the past work encompassing PCS and BOSS devices, which yield rapid switching at the cost of higher optical power, is provided. The mechanism to increase optical gain using minority-carrier reverse-biased diode is provided next that yield simple structure with high gain at the cost of long-term reliability issue due to high electric field. The latter is addressed using the LTT and optothyristor; they yield support for high-voltage and periodic-switching applications but at the cost of latching that complicates turn-off transition. Subsequently, an outline on devices that integrate optical actuation to traditional majority-carrier field-effect structures (e.g., MOSFET, IGBT, MISFET, SIT) has been provided. Since such devices require charge separation while the optical beam comprises charge-neutral photons, indirect device structures are often required for switching or light can be used for

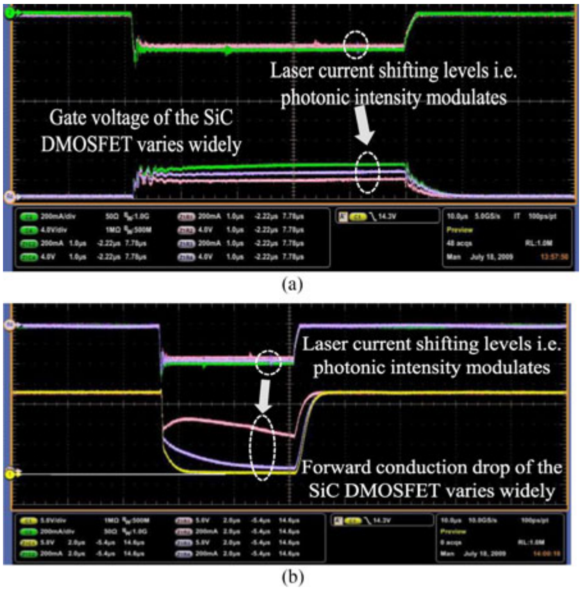


Fig. 20. Experimental demonstration of the OTPT-based photonic modulation of the gate voltage level of the SiC MOSFET and corresponding forward conduction drop variation.

channel-impedance modulation. Based on realizations accrued from the past work, recent and ongoing work that address some of these issues are outlined. These improvements are classified in three categories. First, an all optical monolithic OTPT that leverages III–V direct bandgap material is explored, which address speed while limiting the need for higher optical power. Second, instead of a monolithic approach a separation of functionalities in a hybrid device using a triggering OTPT and a driving power semiconductor device is explored. This enables one to use different material base for the two stages, thereby, optimizing the characteristics and explore both bipolar as well as field-effect devices for the power stage, thereby, optimally addressing gain-speed tradeoff. The third approach is one of scaling the hybrid configuration for very high voltage using an optical SiC-based ETO structure. The latter overcomes the turn-off-speed limitation of the LTT and optothyritors using an intelligently placed OTPT, thereby, yielding much operating frequency even at high voltage. Finally, an outline on the emerging work has been provided that relies on these recent devices outlined previously and some recent GaN-based PCS devices. The focus of this study is primarily on dynamic switching dynamics controllability of these photonically activated devices for yielding multiple system-level benefits for power electronics.

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