

INDUCTIVE ENERGY STORAGE USING A FAST-OPENING BULK OPTICALLY CONTROLLED SEMICONDUCTOR SWITCH (BOSS)

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ABSTRACT

This paper describes the use of the BOSS photoconductive switch as an opening switch in an inductive energy storage circuit consisting of a 200-Ω current-charged transmission line. The BOSS switch, which consists of copper-compensated, silicon-doped, semi-insulating (GaAs:Si:Cu), can be closed and opened on command with two laser pulses of different wavelength. The sustainment of the switch conductance after closing does not require optical energy. The highest voltage gain measured was found to be 10.3 yielding an associated power gain of 106. The highest power that was delivered to the 200-Ω load was 192 kW.

I. INTRODUCTION

Inductive-energy-storage (IES) pulsed-power systems offer many advantages over the more conventional capacitive-energy-storage systems. A primary benefit of an IES system is that the energy storage density of an inductor can be more than an order of magnitude greater than its capacitive counterpart [1]. It has been shown that, rather than using a simple lumped inductor, a current-charged transmission line (CCTL) can be used to store inductive energy [2], [3], [4].

The CCTL is basically a shorted transmission line which behaves as a high-speed, high-Q inductor. After the switch is closed for a length of time equal to t_{charge} , the CCTL of characteristic impedance Z_0 is charged to I_c as shown in Fig. 1(a). The energy ($\frac{1}{2}LI_c^2$) is stored in the total inductance (L) of the transmission line. The current I_c results from the superposition of a positively travelling wave (PTW) and a negative travelling wave (NTW) which are constantly reflected back and forth by the shorted end of the CCTL and the low-impedance voltage source which is comprised of a capacitor (assuming that the switch on-state resistance is zero ohms) as shown in Fig. 1(b). Under these conditions, the current would continue to rise as long as the switch is closed. In a practical circuit there will be both the switch on-state impedance as well as the source impedance to limit the current. During the charging cycle (t_{charge}) the current will exhibit a stair-step behavior with a step amplitude given by $\Delta I_c = 2V_c/Z_0$ and a step width given by the round-trip time (τ) of the CCTL. After the switch opens, thereby interrupting the charging current, the NTW ($I = I_c/2$) is terminated in the matched load resistance (R_L), while the PTW is converted into a NTW at the shorted end of the CCTL [5]. Thus a negative-going square pulse is generated (as shown in Fig. 2) with a pulse width equal to τ and an amplitude given by

$$V_L = \frac{I_c}{2} R_L = V_c \frac{t_{\text{charge}}}{\tau}. \quad (1)$$

Equation 1 clearly shows that the amount of voltage amplification achieved is proportional to the length of time that the switch is closed.

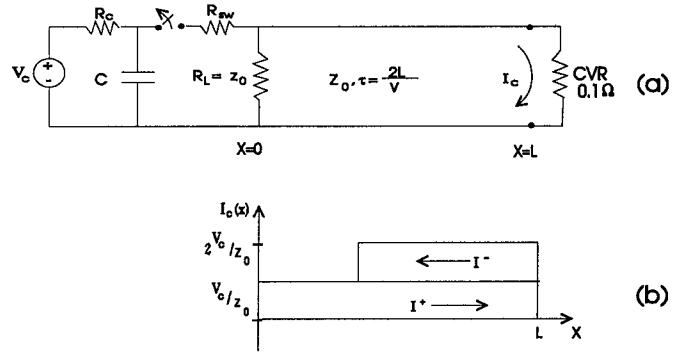


Fig. 1 Current-charged transmission line: (a) schematic diagram, (b) spatial distribution of the current.

The ability to achieve near-ideal voltage amplification in inductive energy circuits depends on the availability of a near-ideal opening switch. For good voltage gain, the switch must open in a time shorter than τ , and have long conduction times with a low on-state impedance. After opening, the switch off-state impedance must be much larger than the R_L to provide proper impedance matching during the discharge cycle of the CCTL. The BOSS photoconductive switch was selected for this application because of its abilities to meet these requirements.

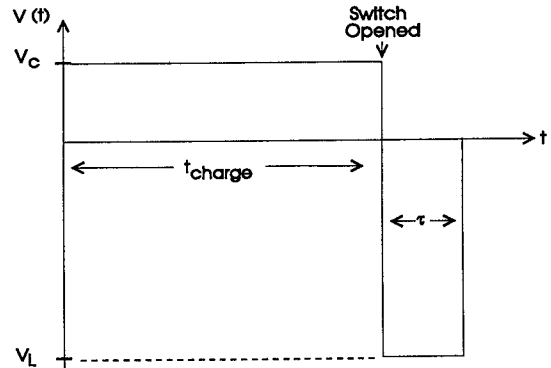


Fig. 2 Theoretical load-voltage waveform generated by a CCTL where τ is the round-trip time and V_c is the charge voltage.

II. THE 'BOSS' OPENING SWITCH

The Bulk (or bistable) Optically controlled Semiconductor Switch (BOSS), relies on persistent photoconductivity followed by photo-quenching to provide both switch closing and opening, respectively [6]. Persistent photoconductivity results from the excitation of electrons from the deep copper centers found in

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1. REPORT DATE JUN 1993	2. REPORT TYPE N/A	3. DATES COVERED -	
4. TITLE AND SUBTITLE Inductive Energy Storage Using A Fast-Opening Bulk Optically Controlled Semiconductor Switch (BOSS)		5a. CONTRACT NUMBER	
		5b. GRANT NUMBER	
		5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)		5d. PROJECT NUMBER	
		5e. TASK NUMBER	
		5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Physical Electronics Research Institute Old Dominion University Norfolk, Virginia 23529-0246		8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S)	
		11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release, distribution unlimited			
13. SUPPLEMENTARY NOTES See also ADM002371. 2013 IEEE Pulsed Power Conference, Digest of Technical Papers 1976-2013, and Abstracts of the 2013 IEEE International Conference on Plasma Science. Held in San Francisco, CA on 16-21 June 2013. U.S. Government or Federal Purpose Rights License.			
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15. SUBJECT TERMS			
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT
a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified	SAR
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copper-compensated, silicon-doped, semi-insulating GaAs (GaAs:Si:Cu). The small cross-section for electron capture back into the Cu centers allows long conduction times (tens of microseconds) after the first laser pulse is terminated. Photoquenching is accomplished by the application of a second laser pulse of longer wavelength which excites holes from the copper levels into the valence band. The free holes rapidly recombine with free electrons to quench the photoconductivity over a time scale given by the electron-hole lifetime of the material. These processes allow a switch to be developed which can be closed by the application of one laser pulse ($\lambda \approx 1 \mu\text{m}$) and opened by the application of a second laser pulse with a wavelength about twice that of the turn-on laser. Optical quenching of photocurrents in excess of 150 A has been demonstrated on the nanosecond time scale [7]. Optical quenching of photocurrents on the subnanosecond time scale has also been demonstrated in low-power BOSS devices [8].

III. SWITCH PREPARATION

Low resistivity, silicon-doped (n-type) GaAs can be converted into semi-insulating material by electrical compensation, that is the introduction of acceptors through a thermal diffusion process. By adjusting the concentration of copper in the n-type material, it is possible to achieve a resistivity as high as $10^8 \Omega\text{-cm}$ at 300 K [9]. One defect, among several formed by copper in GaAs, is a deep acceptor known as Cu_B which is located 0.44 eV above the valence band. The samples used in this investigation were taken from a GaAs crystal grown using the horizontal Bridgman technique [10]. The material was originally doped at a silicon concentration of $\sim 2 \times 10^{16} \text{ cm}^{-3}$ which yielded a resistivity of about $7 \times 10^{-2} \Omega\text{-cm}$. The samples were degreased and RF sputter cleaned prior to the deposition of a $1\text{-}\mu\text{m}$ copper layer on both sides of the crystal. Each sample was then loaded into a quartz ampoule which was loaded with pure arsenic and evacuated to $\sim 10^{-6}$ torr. An arsenic overpressure is provided to minimize the decomposition of the GaAs during the high-temperature anneal. The ampoules were then placed in a diffusion furnace and annealed at 575°C for 6 hours. After the diffusion the ampoules were opened and the samples were polished on both sides to a mirror finish.

The sample dimensions were 12 mm by 10 mm by 0.44 mm thick. A p^+i-n^+ device was manufactured by depositing ohmic contacts that were 1 cm wide and separated by a 5-mm gap on the same side of the sample. The n-type contact metalization was manufactured by RF sputtering a $1000\text{-}\text{\AA}$ Au:Ge (88%:12%) layer, a $250\text{-}\text{\AA}$ nickel layer, and an additional $4000\text{-}\text{\AA}$ Au:Ge layer to reduce the sheet resistance. The p-type contact was manufactured by sputtering 5000 \AA of Au:Zn (85%: 15%). The contacts were then annealed at 450°C for 10 minutes in N_2 at atmospheric pressure. Silver epoxy was used to attach the copper electrical leads to the sample. Dark I-V characteristics of the sample yielded a resistivity of $6 \times 10^4 \Omega\text{-cm}$. This resulted in an increase of the material resistivity by about six orders of magnitude through the electrical compensation process.

IV. EXPERIMENTAL SETUP

When considering the use of a CCTL in a pulsed-power application, the switch on-state resistance becomes a very important parameter. The two primary effects of a non-zero on-state resistance are that the current charging rate is reduced as a result of the forward voltage drop on the switch, and the step increase in the charging current (ΔI_c) is reduced because the reflection coefficient at the switch is less than $\Gamma = -1$. In order to help alleviate these problems the impedance of the CCTL can be

increased. Since it is difficult to obtain high transmission-line impedances, it is possible to connect multiple CCTLs in series to get the desired result [11]. Photoconductivity and photoquenching measurements were performed to evaluate the operation of a BOSS device that was embedded in a $200\text{-}\Omega$ series-connected CCTL as shown in Fig. 3. This CCTL was manufactured by connecting four $50\text{-}\Omega$ strip lines in series with their shields floating. The strip lines were manufactured on a G-10 substrate (dielectric constant = 4.8) and had a round-trip time of 10 ns. The current was measured by a $0.1\text{-}\Omega$ CVR located at the end of the fourth line and the voltage was measured across the $200\text{-}\Omega$ load. For low-voltage DC tests, the voltage source for the CCTL was simply a $1\text{-}\mu\text{F}$ capacitor that was resistively charged. For higher applied voltages it was necessary to replace the capacitor by a pulse-charged $17\text{-}\Omega$, 100 ns PFL. The length of the PFL limited the current charge time (t_{charge}) and thus the voltage amplification of the circuit.

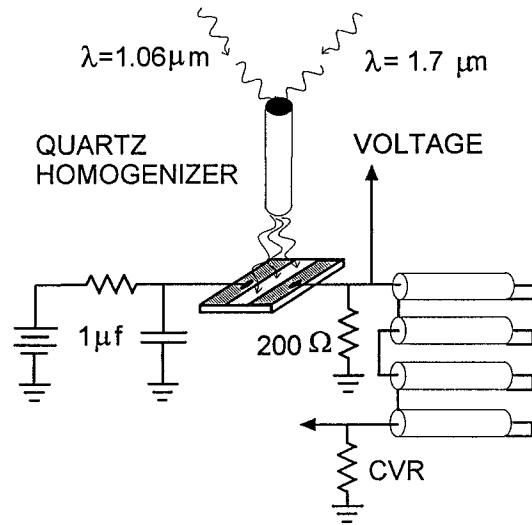


Fig. 3 Schematic of four series-connected, $50\text{-}\Omega$ CCTLs with a total impedance of 200Ω .

Two different laser systems, manufactured by Spectra Physics, were used to generate the closing and opening laser pulses. A Q-switched, DCR-11 Nd:YAG laser ($\lambda = 1.06 \mu\text{m}$, $h\nu = 1.17 \text{ eV}$) was used to close the switch. The output of this laser was passed through a dye cell (containing Q-switch II laser dye) to sharpen the laser-pulse rise time to less than 1 ns and reduce the tail of the pulse to yield a FWHM of 1.8 ns with a pulse energy, incident on switch, of about 10 mJ (11 MW/cm^2). The "turn-off" laser pulse ($\lambda = 1.7 \mu\text{m}$, $h\nu = 0.73 \text{ eV}$) was generated by a DCR-3 Nd:YAG laser in conjunction with a pulsed dye laser and an IR-WEX LiNbO_3 mixing crystal. This laser had a FWHM of 2.5 ns and a pulse energy of 2.5 mJ (2 MW/cm^2) incident on the switch. As shown in Fig. 3, the laser pulses were guided to the switch by a quartz homogenizer which was used to remove most of the spatial mode structure.

V. EXPERIMENTAL RESULTS

Experiments were performed using the circuit shown in Fig. 3 at relatively low DC bias voltages ranging from 50 to 250 V. Figure 4 illustrates the superposition of three different switching transients for an applied voltage of -50 V and with the variable parameter being the charge time (t_{charge}). As expected, when the

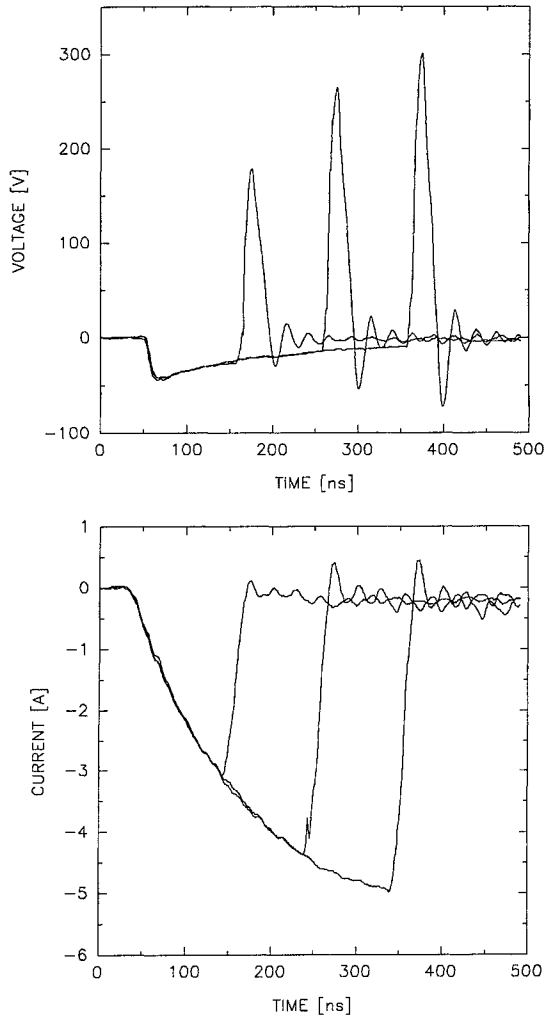


Fig. 4 Superposition of three output waveforms for an applied DC bias of 50 V and with the current-charging time as the variable parameter.

current-charge time was increased, the amplitude of the generated voltage pulse increased. Note that the measured voltage pulse is not as high as that predicted by Eqn. 1. This is the result of the switch on-state resistance, as mentioned earlier, as well as the result of the several-nanosecond opening time of the BOSS switch. This opening time is controlled by both the laser parameters (rise time and energy) and the deep-level parameters of the BOSS device. Research is presently being conducted to enhance the opening effect in BOSS devices by re-engineering the bandgap of the bulk material [12]. If the switch were to open in less than 1 ns the voltage amplification of the circuit would be greatly enhanced.

A higher-voltage waveform is illustrated in Fig. 5 for a DC bias of 225 V. The amplitude of the voltage pulse was measured to be 2200 V yielding a voltage gain of 9.8 and an associated power gain of 96. The highest voltage gain achieved with this circuit was 10.3 yielding a power gain of 106. This is to our knowledge, the highest power gain realized in a CCTL.

A 17- Ω PFL was used in lieu of the capacitor in Fig. 3 to investigate the operation of the CCTL at higher voltages. In this circuit, the current-charging rate is further reduced by the higher source impedance. An example of a current and voltage waveform from the modified circuit is shown in Fig. 6 for an applied bias voltage of 1.9 kV. The voltage multiplication factor for this waveform was found to be 2.9 yielding an amplitude of 5.5

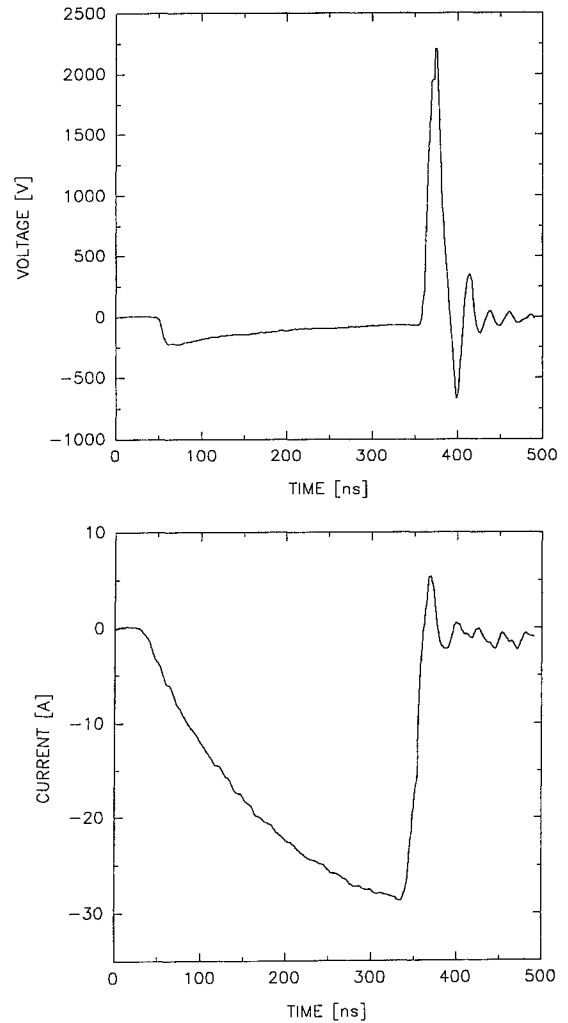


Fig. 5 Output waveforms of the CCTL for an applied DC bias of 225 V. The peak voltage generated was 2.2 kV yielding a voltage amplification of 9.8 and a power gain of 96.

kV and a power gain of 8.4. The generated pulse width was reduced because the switch starting to break down (filament) while the voltage was being reestablished across it. The maximum voltage that was delivered to the 200- Ω load was 6.2 kV or a peak power of 192 kW. This is also, to our knowledge, the highest peak power level that was delivered to the load of a CCTL.

VI. CONCLUSION

We have demonstrated the use of a BOSS device for the opening switch in an inductive-energy-storage circuit called the current-charged transmission line. Voltage amplification factors as high as 10.3 were obtained which yielded a power gain of 106. The maximum voltage that was generated across the CCTL 200- Ω load was 6.2 kV yielding a peak power level of 192 kW. The voltage gain was primarily limited by the opening time of the BOSS device which was on the order of 5 ns. The peak power that could be obtained was limited by the transition of the switch into filamentary conduction during the reestablishment of the voltage. Future improvements to the BOSS switch should greatly improve its performance and applicability in inductive-energy-storage circuits.

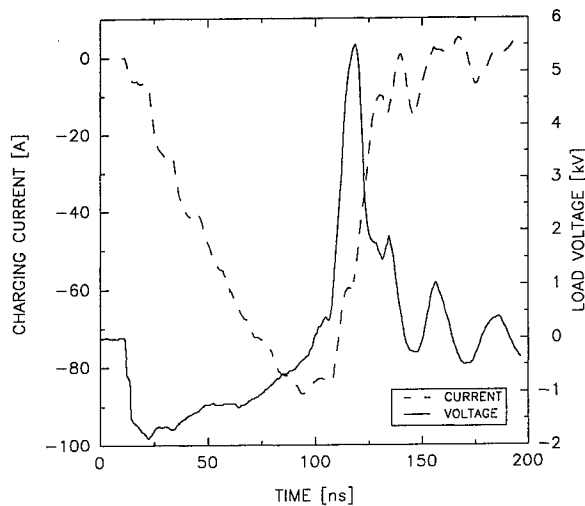


Fig. 6 Output waveforms of the CCTL for an applied bias of 1.9 kV. The peak voltage was 5.5 kV corresponding to a peak power of 151 kW.

ACKNOWLEDGEMENTS

This work is supported by the Space and Naval Warfare Systems Command (SPAWAR 232) and by SDIO/IST, managed by ONR.

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