

High Gain GaAs Photoconductive Semiconductor Switches for Impulse Sources†

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ABSTRACT

A high peak power impulse pulser that is controlled with high gain, optically triggered GaAs Photoconductive Semiconductor Switches (PCSS) has been constructed and tested. The system has a short $50\ \Omega$ line that is charged to 100 kV and discharged through the switch when the switch is triggered with as little as 90 nJ of laser energy. We have demonstrated that the GaAs switches can be used to produce either a monocycle or a monopulse with a period or total duration of about 3 ns. For the monopulse, the voltage switched was above 100 kV, producing a peak power of about 48 MW to the $30\ \Omega$ load at a burst repetition rate of 1 kHz. The laser that is used is a small laser diode array whose output is delivered through a fiber to the switch. The current in the system has rise times of 430 ps and a pulse width of 1.4 ns when two laser diode arrays are used to trigger the switch. The small trigger energy and switch jitter are due to a high gain switching mechanism in GaAs.

Keywords: Photoconductive semiconductor switch, GaAs, high gain, impulse sources, lock-on.

1. INTRODUCTION

This research has focused on optically triggered, high gain GaAs switches for impulse sources for ultrawide bandwidth transmitters. The practical significance of this high gain switching mode is that the switches can be activated with very low energy optical triggers allowing for compact sources.¹ For example, this work will show that a 90 nJ optical pulse has triggered switches that have delivered 48 MW in a $30\text{-}50\ \Omega$ system, and previously we have switched 6 MW for ~ 100 ns in a $0.25\ \Omega$ system.² The GaAs switches used in this experiment are lateral switches: they have two contacts on one side of a wafer separated by an insulating region of intrinsic material. At electric fields below 4 kV/cm, the GaAs switches are activated by the creation of, at most, one electron hole pair per photon absorbed. This linear mode demands high laser power, and after the light is extinguished, the carrier density decays in 1- 10 ns. At higher electric fields these switches behave very differently. The high field induces carrier multiplication so that the amount of light required is reduced by as much as five orders of magnitude.^{1,2} This high gain mode is characterized by fast current rise times (~ 200 ps) and filamentary currents with densities of several MA/cm² and diameters of 15- 300 μm (from the photographs of recombination radiation). In the "on" state there is a characteristic, constant field across the switch called the lock-on field. The switch current is circuit-limited provided the circuit maintains the lock-on field.² As the field increases, the switch risetime decreases and the trigger energy is reduced.² During high gain switching the switches emit bandgap radiation. When this radiation is imaged, filaments are observed, even if the triggering radiation is uniform.^{3,4} Table I shows the results from this experiment and the best results that we have achieved (in other work) with the high gain GaAs switches when triggered with either compact laser diode arrays or with flashlamp-pumped lasers. The work of many others has been presented at various conferences.⁵

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Table I Parameter	This Experiment	Other Tests*
Switch Voltage (kV)	100	155
Switch Current (kA)	1.26	5.2
Peak Power (MW)	48	120
Rise time (ps)	430	430
R-M-S jitter (ps)	150	150
Optical Trigger Energy (nJ)	180	90
Repetition Rate (Hz)	1,000	1,000
Electric Field (kV/cm)	67	100
Device Lifetime (# pulses)	$5 \times 10^{4\#}$	6×10^6

* Not all the results are simultaneous.

The 50,000 pulses were achieved at a voltage of 77 kV.

Table I. Results of tests with high gain GaAs switches. The first column is this work only, the second column includes results of previous tests.

2. IMPULSE SYSTEM

The circuit that was used in these tests is shown in Figure 1. It operated in bursts of up to 5 pulses at a repetition rate of 1 kHz. We charged a nominally 1.0 ns long, 47 Ω , parallel plate transmission line to voltages of about 100 kV. This line is discharged with either one or two switches into a 30 Ω load. We measured the voltage on the transmission line and the current through the load. A typical transmission line voltage waveform is shown in Figure 2a. The voltage on the line rose to a peak value with a risetime of 210 ns. At this point the laser activated the switch and the line voltage dropped. If only one switch was triggered, the resulting load voltage was a monopulse. If both switches were triggered simultaneously the load current was a monocycle (bipolar pulse). The switches were fabricated from undoped GaAs with Ni-Ge-Au-Ni-Au metallization. Their insulating region separating the two contacts was 1.5 cm, the total contact width was 7.6 cm. Because of the high electric fields the switches were immersed in a dielectric liquid (Fluorinert®). To avoid corona and breakdown, the transmission line was in SF₆ gas.

For most of the experiment two laser diode arrays were used to trigger the switches. Each consisted of three laser diodes coupled to a 400 μ m fiber optic. Each array delivered 90 nJ in 4.2 ns at 876 and 857 nm to a spot near the negative high voltage (100 kV) side of the switch. Figure 3 shows the laser waveform. For other tests, these same laser diode arrays were configured to produce a longer pulse (20 ns) with larger energy (1.8 μ J) and power (90 W).

All the monitors were calibrated. The calibration of the low bandwidth voltage monitor was straightforward. The actual dynamic resistance of the load was measured to be 30 Ω . The peak power is then 48 MW. Using the charge voltage of 100 kV and an estimate of the switch voltage drop of 9 to 6 kV, the peak power is 42 to 45 MW for the 30 Ω load.

3. RESULTS- CURRENT WAVEFORMS

In the first set of tests both laser diode arrays were used to activate one switch and obtain a monopulse. The highest current measured with this system is shown in Figure 4. The width of the current pulse and its peak value depend on the time delay between when the two laser diodes are triggered. When both diodes are triggered to produce simultaneous current pulses, the current is largest and the current pulse width is smallest. The highest current was 1.26 kA with a rise time of 430 ps and a pulse width of 1.4 ns. The peak power is 48 MW. With one laser diode activating one switch the current is about 1.0 to 1.1 kA with a rise

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time of about 770 ps and a pulse width of 1.7 -1.9 ns. Figure 5 is a plot of the average over multiple pulses of the peak current and the current pulse width as a function of the delay between the activation of the arrays. Note that in order to achieve higher currents than those achieved with one laser diode, both laser diodes must trigger within ± 400 ps each other. Also note that the improvement in the current is about 10%.

The difference in current waveforms when we use one laser versus two may be due to two different reasons: a difference in the switch inductance and a the dynamics of the high gain process. Our circuit simulations show that the current risetime for a total inductance of 18 nH would be about 430 ps with a width of 1.3 ns. An inductance of 40 nH results in a rise time of 740 ps with a width of 1.6 ns. Thus it may be possible that one filament with an inductance of 40 nH results in one current waveform and two filaments with about half the inductance create a faster current pulse with a faster rise and smaller width. The problem with this scenario is that the inductance we expect, based on the pictures of the filaments that gave rise to these current waveforms, is much smaller: 4 nH. Thus, other factors contribute to the different waveforms. One possibility is that the gain in one filament may be affected by the presence of the other filament resulting in a faster process: the lower current density in each filament may allow it to create more carriers, especially if there is an upper bound in the carrier density. Another possibility is that both filaments are generating carriers and thus the time required for their combined resistance to drop is reduced by a factor of two.

The second set of tests utilized both laser diodes, each triggering one switch, to produce a monocycle. Figure 6 shows the current waveform: In theory, with ideal switching, the monocycle should be composed of two monopulses of opposite polarity each with half the pulse width. Thus, we expect a monocycle composed of a negative and positive pulses with a width (each) of 0.9 ns. What we observe is a width of 1.0 ns for the negative pulse and 1.3 ns for the positive pulse. The reason for this is a timing error of about 200 ps. The minimum width should occur when both switches are triggered simultaneously. It is very important to trigger both switches at the same time to obtain full voltage and to obtain the proper waveform. In our tests, the switch jitter did not allow us to always reproduce the monocycle.

Low jitter triggering at 90 to 180 nJ of optical energy depends on the rise time of the pulse charging (voltage) waveform. We tested this effect in a experiment where the first to last timing spread was recorded for different voltage rise times (210, 590, and 865 ns) and different laser energies (90 nJ and 1.8 μ J). The three voltage waveforms are shown in figure 2. Neither laser energy triggered the switch with the 865 ns rise time. The 90 nJ did not trigger the switch when the voltage rise time was 590 ns. The 1.8 μ J did trigger the switch when the rise time was 590 ns but only about half the time. The first to last timing spread was 6 ns for one ten pulse sequence and up to 100 ns in others. For the 213 ns rise time both laser energies resulted in timing spreads of < 1 ns. The experiment shows a relationship between the rise time of the voltage across the switch, the required trigger energy, and switch jitter. This is opposite to the switch rise time for linear photoconductivity where the drop in switch resistance is dependent only on the laser pulse and the carrier lifetime. Note that the dielectric relaxation time, $\rho\epsilon$, is 11.6 μ s. Thus, these effects are occurring at times that are much shorter than the relaxation time. It may be possible that the effect that we observe is related to trap filling in the GaAs because trap filling affects the electric field distribution.

4. SWITCH LONGEVITY

Given that the high gain switches are capable of producing this type of current pulses, it is important to understand the mechanisms that damage the switches to be able to predict their longevity. The mechanisms that may result in damage to the PCSS are many. Initiation of the final breakdown appears to come from regions near the contacts which have been significantly damaged during previous pulses. To test for switch longevity we have performed extensive switch longevity tests.^{6,7} As part of these tests we tested the longevity of the switches at high current in this system. We switched 77 kV,

obtaining 50,000 pulses with a peak current of 600 to 650 A. The laser operated at 1 Hz, and uniformly illuminated the switch, producing multiple filaments⁸ (at least 10).

A companion paper in this conference⁷ discusses the results of testing the switches at voltages of up to 10 kV. Many different metallizations and switch geometries were tested to determine the wear mechanism and the best contact metallization. A pulsed power source charged a 50 Ω coaxial cable to 1.7 or 3.3 kV in 100 ns to 1 μ s. This was discharged by the switch (1 mm long by 5 mm wide) into a 50 Ω load producing a current pulse of 10.5 A (for 1.7 kV) or 23 A (for 3.3 kV) with a duration of 3.5 ns. The switches have lasted up to 4 million pulses under these conditions.

5. CONCLUSION

This study has shown that it is possible to obtain high peak power (48 MW) impulses in a system with an impedance of 30- 50 Ω using laser diode triggered PCSS operated in the high gain mode. The system was operated at a burst repetition rate of 1 kHz. The system is very small because laser diode arrays of very small energy output (90 nJ) were utilized to trigger the switches. The ability of the laser diodes to trigger the switches was enhanced by fast (210 ns) charging of the transmission line which the switch discharges. An added benefit of the faster charging was a small switch jitter (150 ps). The small jitter may allow the use of these pulsers in transmitter arrays.

6. ACKNOWLEDGMENT

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7. REFERENCES

- [1] G. M. Loubriel, M. W. O'Malley, and F. J. Zutavern, "Toward Pulsed Power Uses for Photoconductive Semiconductor Switches: Closing Switches," Proc. 6th IEEE Pulsed Power Conference, P. J. Turchi and B. H. Bernstein, eds., Arlington, VA, 1987, p. 145.
- [2] F. J. Zutavern and G. M. Loubriel, "High Voltage Lateral Switches from Si or GaAs," High-Power Optically Activated Solid-State Switches, A. Rosen and F. J. Zutavern, Eds., Artech House, Boston, 1993, p. 245.
- [3] R. A. Falk, J. C. Adams, and G. L. Bohnhoff-Hlavacek, "Optical Probe Techniques for Avalanching Photoconductors," Proc. 8th IEEE Pulsed Power Conference, R. White and K. R. Prestwich, eds., San Diego, CA, 1991, p. 29.
- [4] F. J. Zutavern, G. M. Loubriel, M. W. O'Malley, W. D. Helgeson, and D. L. McLaughlin, "High Gain Photoconductive Semiconductor Switching," Proc. 8th IEEE Pulsed Power Conference, R. White and K. R. Prestwich, eds., San Diego, CA, 1991, p. 23.
- [5] See Proceedings from: 6-8th IEEE Pulsed Power Conf., 1987, 1989, 1991; 18-20th IEEE Power Modulator Symposium, 1988, 1990, 1992; SPIE Optically Activated Switching I-III, (vol. 1378, 1632, 1873), 1990, 1992, 1993; and IEEE Trans. Elec. Devices, (vol. 37, 38), 1990, 1992.

[6] G. M. Loubriel, F. J. Zutavern, H. P. Hjalmarson, R. R. Gallegos, W. D. Helgeson, and M. W. O'Malley, "Measurement of the Velocity of Current Filaments in Optically Triggered, High Gain GaAs Switches," Applied Physics Letters, Vol. 64, No. 24, 1994, p. 3323.

[7] F. J. Zutavern, G M. Loubriel, H. P. Hjalmarson, A. G. Baca, T. A. Plut, R. R. Gallegos, W. D. Helgeson, and M. W. O'Malley, "High Gain GaAs Photoconductive Semiconductor Switches (PCSS): Device Lifetime, High Current Testing, Optical Pulse Generators," to be published in Proc. of SPIE Optically Activated Switching Conference IV, SPIE Proc. Series Vol. 2343, W. R. Donaldson, ed., Boston, MA, October 31-November 4, 1994.

[8] G. M. Loubriel, F. J. Zutavern, M. W. O'Malley, and W. D. Helgeson, "High Gain GaAs Photoconductive Semiconductor Switches: Measurement of Filament Velocity and Reduced Trigger Energy," to be published in Proc. of SPIE Optically Activated Switching Conference IV, SPIE Proc. Series Vol. 2343, W. R. Donaldson, ed., Boston, MA, October 31-November 4, 1994.

Figures

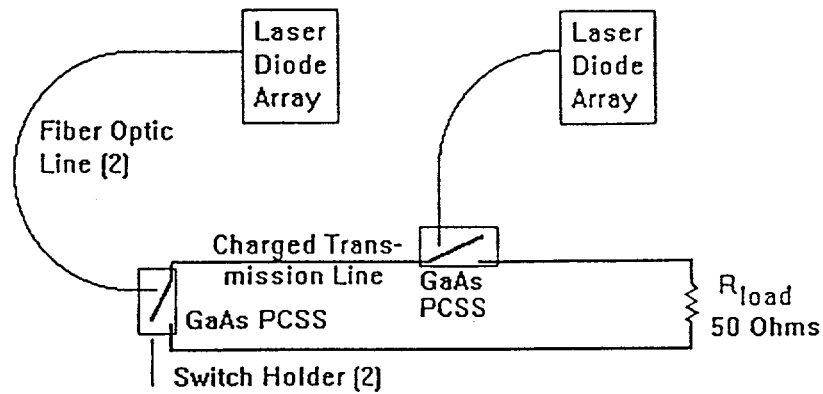


Figure 1. Schematic of the circuit that was used in these experiments. A short (1 ns), 47 Ω transmission line (the charge line) was charged to high voltage at a burst repetition rate of 1 kHz. Two switches were used on either side of the line to discharge the line into a 30 Ω load.

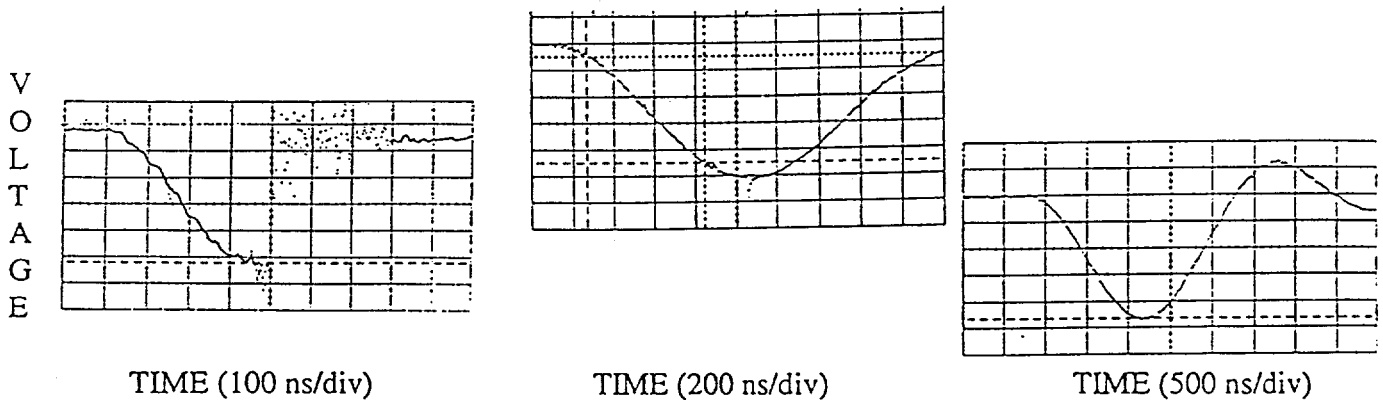


Figure 2. The voltage on the charge line for three different system configurations. The waveforms are displayed at 20 kV/div. The peak voltage is 100 kV. In the waveform to the left the laser triggers the switch at the peak of the voltage waveform. In a) the voltage risetime is 210 ns, in b) and c) it is 590 ns and 865 ns, respectively.

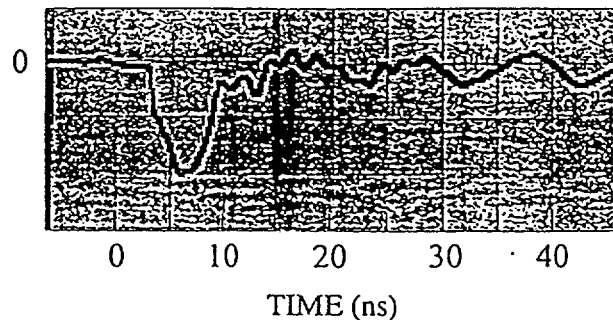


Figure 3. Laser pulse waveform of the fiber-optic coupled, small laser diode array. The total energy in the pulse is 90 nJ in a pulse whose width is 4.2 ns.

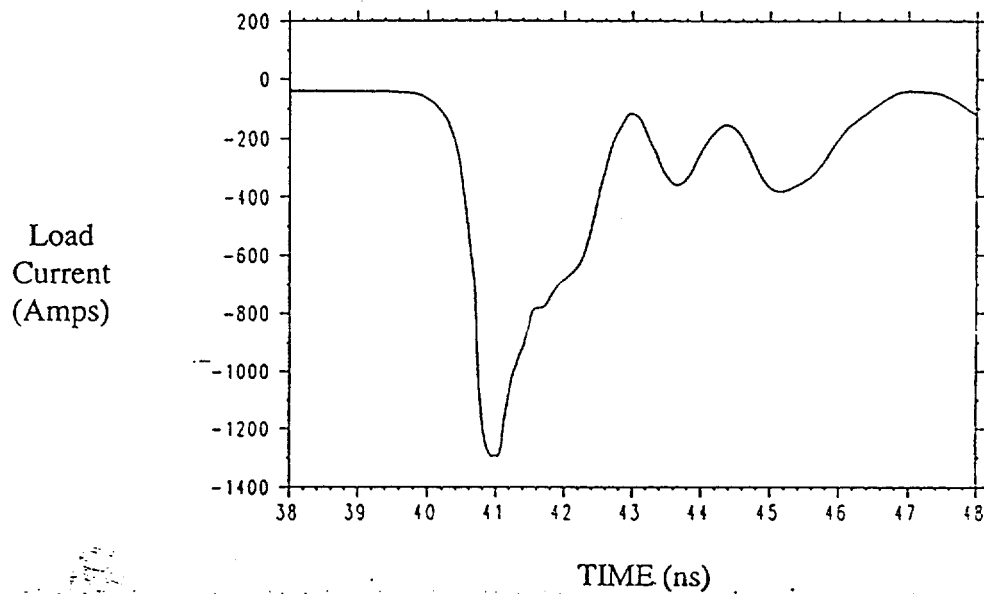


Figure 4. The current through the $30\ \Omega$ load when both laser diodes illuminate one switch: 1:26 kA peak (48 MW), 430 ps rise, 1.4 ns wide.

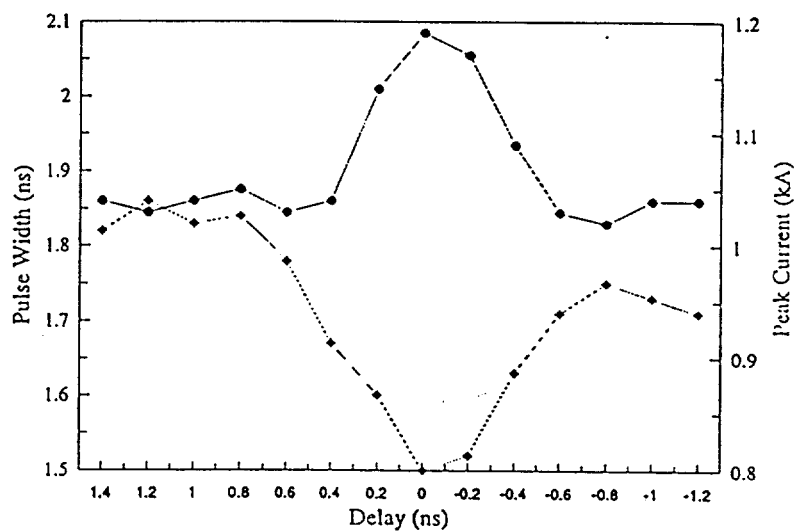


Figure 5. . The peak current (●) and pulse width (◆) as a function of the delay between the laser diode arrays. Each point represents an average of those values for a given delay.

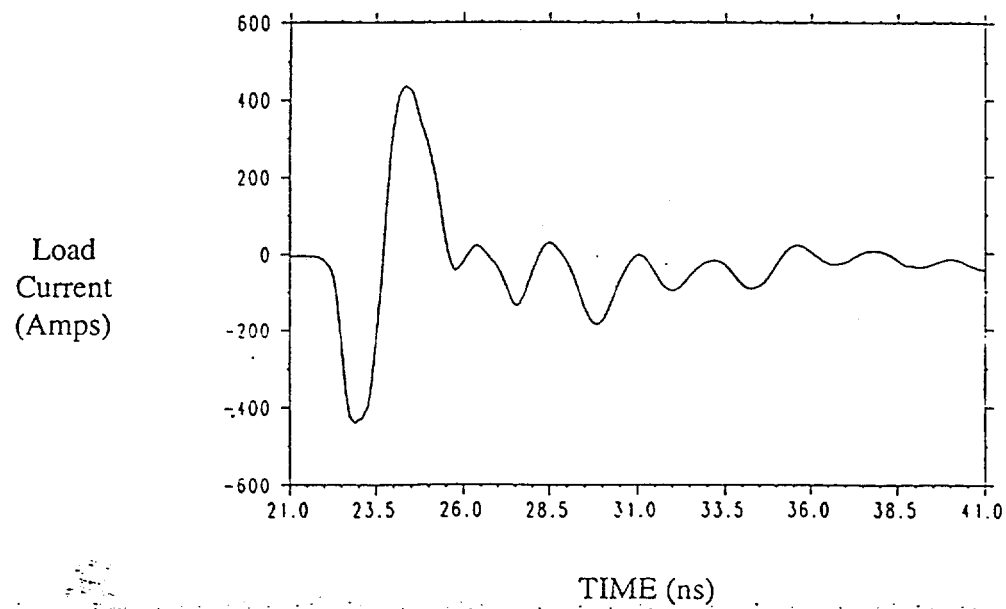


Figure 6. The current through the $30\ \Omega$ load when each of the two laser diodes is used to trigger one switch.