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High Gain GaAs Photoconductive Semiconductor Switches (PCSS): Device Lifetime, High Current Testing, Optical Pulse Generators[♦]

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Abstract

This paper presents results from three areas of GaAs PCSS research and development: device lifetime, high current switching, and PCSS-driven laser diode arrays (LDA). We have performed device lifetime tests on both lateral and vertical switches as a function of current amplitude, pulse width, and charging time. At present, our longest-lived switch reached 4×10^6 pulses. Scanning electron microscope (SEM) images show damage near the contacts even after only 5 pulses. We are presently searching for the threshold at which no damage is evident after a single shot. In high current tests, we have reached 5.2 kA at 4.2 kV. This was achieved using twenty fiber-optic coupled lasers to distribute current filaments over a 5 mm wide PCSS. Current waveforms and images of the current filaments as a function of current amplitude will be presented. The lasers used to trigger the high current PCSS were driven with a miniature PCSS. Low inductance, high speed GaAs PCSS are very effective as short pulse laser diode array drivers. Some types of arrays gain switch, producing a compressed optical pulse which is only 75 ps wide. Results from tests with a variety of laser diode arrays will be presented.

Keywords: switches, photoconductivity, optical activation, gallium arsenide, high current, high voltage, high speed, high power, laser diodes, semiconductor lasers, short pulse lasers.

1. Introduction

High gain GaAs PCSS have the ability to control many Joules of electrical energy with only a few micro-joules of optical trigger energy. This paper discusses three different aspects of this capability. Switch longevity is reported for a variety of test conditions. Many factors which influence device degradation were tested, and results from these tests are described. Switch performance at high currents (5 kA) and relatively long pulses (100 ns) was improved by using fiber-optic coupled laser diode arrays (LDA) to initiate multiple current filaments and distribute the current across the switch. The LDA which trigger our large PCSS are low impedance loads and hence difficult to pulse rapidly. Miniature PCSS are used to drive the LDA, and the properties of these optical pulse generators described.

2. Device Lifetime

Many of the factors which influence PCSS lifetime are shown in Table I. For convenience of discussion, these factors are grouped into three categories: circuit, trigger, and switch properties. The factors are highly interdependent. For example anything that makes triggering easier, such as reduced charging pulse rise time, will allow triggering at lower voltages and or optical trigger energies, i.e. it reduces their thresholds. Even if all other parameters are held constant, a factor which reduces the thresholds of other factors may be influencing switch lifetime indirectly. A second point is that switch lifetime is a "weak link" problem. Whenever an improvement is made, all other factors need to be revisited in order to determine their

Table I. Factors which influence PCSS lifetime.

circuit properties	trigger properties	switch properties
initial switch voltage	optical energy	length
switch current	optical pulse width	width
switch current pulse width	spatial distribution	dark resistivity
charging pulse rise time	wavelength	contact configuration
"recharge" current	spectral width	contact metallization
repetition rate		contact polarity
dielectric near switch		coatings
field shape near switch		sub-surface region

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relative importance. Improvements in an n-type contact cannot improve switch lifetime, if the p-type contact on the other side of the switch is eroding to the point that surface flashover is being initiated.

In principle, each of the factors could be tested as a variable, while the others are stepped (one at a time) over a range of values. Even if only five values were considered for each range, a total of $5^{21} = 5 \times 10^{14}$ lifetime tests would be possible, with each test consisting of up to several million pulses, depending upon the rate of degradation. To limit the scope of this problem, we have made several assumptions and restricted our testing to only a few variables while all others are held to a more reasonable factor space. One assumption is that reasonable information about our large high power switches can be obtained by testing smaller switches which are scaled down in the dimensions that control voltage and current handling capacity. In this paper, we will call the dimension that controls voltage "length" and the dimension that controls current "width". If this assumption is valid, results from these tests can be applied to larger switches which are operated at similar electric fields and current densities (current per unit of switch width). Since the current during high gain switching is always confined to filaments,^{1,2,3} and multiple filaments can be initiated with relative independence,^{4,5,6} another more accurate assumption about current scaling may be that switch degradation will scale with the current per filament. High current switches may yield lifetimes, which depend inversely on the number of filaments generated per pulse, or they may yield lifetimes which are comparable to those of small switches when the currents per filament are comparable. It is not the purpose of this paper to validate these assumptions, but rather to use them as a starting point, with the intention to test their validity as specific applications for higher currents and voltages are pursued. With these assumptions in mind, results are presented from lifetime tests with switches of 0.5-5 mm in length and width, which were operated at 5-250 A and 0.5-20 kV. (All switches are 0.5-0.6 mm thick.) Our interests range to individual switches with either dimension as large as 35 mm and banks of switches which could handle 20-40 kA and 500-1,000 kV.⁷

The longest lifetime, 4×10^6 pulses, was achieved by optimizing several of the factors listed in table I. Switch current was 10 A (peak) in a 3 ns wide pulse. The charging pulse had a 1 μ s rise time to 1.5 kV followed by a 1.5 μ s delay before triggering the PCSS. The charging circuit was isolated from the transmission line which the PCSS discharged by a string of high voltage, high speed diodes. The diodes and 1.5 μ s isolating delay allowed the charging pulse to dissipate while holding the charge on the test transmission line. This technique avoids any "recharging" current from the pulser after the switch is triggered. Such low level, but long duration current may be very destructive to the PCSS during its recovery phase. The switch, shown in figure 1 (lower photo), was 1 mm long (horizontal in photo) by 5 mm wide with contacts made from an

annealed Au:Ge alloy. The switch was coated with a dielectric varnish and submerged in Flourinert (3M) to prevent premature surface flashover. It was triggered repetitively at 400 Hz with a 876 nm optical pulse from a fiber-optic coupled 3-laser diode array which produced 2 μ J in 5 ns. Usually, a single filament was induced during each pulse. The filament was confined to a 1 mm region which was illuminated by the fiber optic. The fiber was periodically moved to different positions along the 5 mm wide contacts.

Figure 1. GaAs PCSS after 10^5 (upper) and 4×10^6 (lower) test pulses. The photos show only a portion of the 1×5 mm switches. Au:Ge was used for both contacts: cathode (left) and anode (right). Other parameters were: 10 A, 3 ns current pulse; coated surface; 200-400 Hz rep-rate.

Switch damage accumulates gradually near the contacts as the switches are pulsed, until a track develops across the surface which shorts the contacts. Figure 1 shows the surface of two switches under similar test conditions after different numbers of test pulses. Both contacts were made with Au:Ge which makes a good n-type contact. As shown in the photos, damage was greater near the anode than the cathode. Upon examination with electron microscopy, evidence for damage near a contact was found even after only one test pulse under these conditions. Reduction or elimination of this damage may be obtained by a further reduction in current. However, since this switch was operating near its triggering threshold, reduced voltages are not an option without increasing the amount of

optical trigger energy or some other compensating parameter. A higher impedance transmission line can be used to limit the current, but since its capacitance would be reduced (all other parameters held constant), its charge holding capability would be reduced, and the voltage droop would be larger during the isolating delay. This is another example of the interdependence of the factors listed in Table I. The conditions for eliminating the damage per filament per pulse are being pursued, because if they exist, they would represent a threshold improvement in lifetime.

Most of our experience has been with lateral switches (where both contacts are on the same surface of the semiconductor). However, examples of vertical switches which we have tested are shown in figure 2. These switches had a horseshoe shaped Au:Be contact for the anode which was illuminated (visible in the photo), and a filled rectangular Au:Ge contact on the bottom surface for the cathode. They were tested at 20-30 A for 600 (upper photo) and 5×10^5 (lower photo) 3 ns long current pulses. Although these switches lasted a relatively long time, the damage that accumulated was unexpected, considering that the electric field should be mostly perpendicular to this surface. The source or cause of this damage is yet to be determined.

Some examples of other factors which were singled out for testing are shown in figures 3-5. These figures show A-B comparisons of surface damage for switches tested with: (3) different current pulse widths, (4) different peak currents (and corresponding initial voltages), and (5) different contact alloys⁸. All switches in figures 3 and 4 are similar to those shown in figure 1, 1 mm long by 5 mm wide with Au:Ge contacts. In figure 5, one of the contacts on each switch was Au:Be and the dimensions were $1 \times 2.5 \text{ mm}^2$. In all photos (except figure 2) the cathode is on the left.

Figure 2. Unusual surface damage that accumulated on a vertical switch is shown in these photos after 600 (upper) and 5×10^5 (lower) 3 ns long test pulses at 20-30 A. The horseshoe shaped structure is a Au:Be contact on the anode.

Figure 3 The effects of different current pulse lengths, 3 ns (left) and 30 ns (right), after 10^5 test pulses. Other parameters were: 10 A peak current, uncoated surfaces, 100-400 Hz. Coating (see figure 1) inhibits some erosion into the contact.

Figure 4. The effects of different peak currents, 33 A (left) and 43 A (right), after 10^5 , 3 ns long test pulses. Other parameters were: 100 Hz and coated surfaces. Even with coating, erosion extends into the metallization. (Compare to figures 1 and 2.)

Figure 5. The effects of different contact polarities. In both switches, the cathode is on the left, but the left switch (10^5 shots) is an n-i-n made with Au:Ge, and the right switch (12,000 shots) is a p-i-p made from Au:Be. The forward biased contact shows the least damage. Although there is some surface tracking near the Au:Be anode (far right) there is much less contact erosion than on the Au:Ge anode. (The center regions of both switches were omitted.)

Switch current, induced by a single fiber, was varied at constant voltage by using a variable impedance transmission line. Waveforms are shown in figure 6 for impedances ranging from 7 to 50 Ω . Unfortunately the pulse also gets wider as the line is changed. Lifetime tests were performed on one switch at each of these impedances. The results are shown in figure 7.

Figure 6. Currents are shown for switches at constant voltage with a variable impedance transmission line.

Figure 7. Switch lifetimes are shown as a function of their peak current at constant voltage. (See figure 6.)

3. High Current Switching

The application for this work was the development of optically activated electrical firesets. Firesets are the high current circuits used to detonate explosives. This is a low impedance application, where the current is limited by the inductance in the circuit. Figure 8 illustrates this circuit using a PCSS, which is triggered with illumination from a fiber-optic coupled LDA. The low inductance capacitor (210 nF) and copper foil connections in this circuit amount to a total circuit inductance of 25 nH. The original PCSS dimensions were 2 mm long (parallel to the current path) by 30 mm wide and 0.625 mm thick. If current passed uniformly through this region, the switch inductance would be less than 0.1 nH. However, when current filaments form, switch inductance can be much higher. A 1 μ m diameter filament that is a few mm from the ground plane has a few nH of inductance. Concentration of the current near the contacts also produces larger power losses if one assumes a fixed contact resistivity. Under almost any assumptions, concentrated current near the contacts deposits more energy per unit volume and increases contact degradation. Before current filamentation was demonstrated in high gain PCSS, it was assumed that uniform illumination would produce relatively uniform current flow. When filaments were shown to be present during high gain switching, controlling their number and location became a key issue.

Figure 8. The optically activated electrical fireset uses a fiber-optic coupled laser diode array to trigger multiple current filaments in a uniform configuration across the switch.

obtained with a 30 mm wide switch using uniform illumination before current filaments had been discovered. No IR images were being recorded during the original experiments, but damage near the contacts indicated that the current was actually concentrated in a few small regions of the switch.

The images in figure 9 show the concentration of current in a GaAs PCSS when triggered with uniform optical illumination. As the current is increased, many filaments are formed, but they are concentrated near the edges of the switch. These images were obtained with a 5 mm wide switch. The original results for the fireset application (4.2 kA at 4.6 kV) were

Figure 9. These IR images (negative prints) show the current flow in a PCSS which was uniformly illuminated. Switch A ($1 \times 5 \text{ mm}^2$) is conducting 600 A, and switch B ($2 \times 5 \text{ mm}^2$) is conducting 1920 A.

Control of filament locations was demonstrated with low divergence laser beams which were focused either directly on the PCSS or through 1 mm diameter fibers.²⁻⁴ This work also showed that filaments could be triggered most easily near the contacts. Optical triggering required roughly 100 times more light when it was uniform than when it was focused to a 1 mm spot on these $15 \times 20 \text{ mm}^2$ PCSS. Figure 8 shows the new approach to optically activated electrical firesets. In this diagram, the LDA is coupled to the PCSS with a ribbon of fiber-optics. The fibers capture the power density produced near the lasers and deliver it to the PCSS surface near the contact boundaries. This results in more efficient use of the optical energy and more uniform current flow. The images in figure 10 show results of this technique when distributing current across $2 \times 5 \text{ mm}^2$.

Figure 10. These IR images (negative prints) show the current flow produced in a PCSS with fiber-optic triggering. The currents switched are: 220 A (A), 660 A (B), 1.1 kA (C), 2 kA (D).

Figure 11. IR images (negative prints) of a PCSS (A) 33 ms before, (B) during, and (C) 33 ms after a 5.2 kA current pulse. Current filaments fill the entire switch. Comparison of frames A and C show a change in the color and texture of the contacts.

Initially, two fibers were used to trigger each filament. The fibers were located at the ends of the filaments near contacts to control their location with the minimum amount of optical trigger energy. At low currents, filaments were not always triggered at every fiber. Triggering was also very sensitive to the precise location of the fibers near the edges of the contacts. However, as the current was increased, many filaments formed at each fiber. By the time 5 kA was reached (figure 11), the current flow filled the entire switch. The increased current produces such a bright image that the detail of multiple filaments is washed out.

Our previous results with uniform illumination, 4.2 kA in a 30 mm wide switch at 4.6 kV, were produced with 200 μ J of optical trigger energy delivered in 200 ns. The fiber-optic coupled fireset used a 5 mm wide switch which produced 5.2 kA at 4.0 kV with 1.5 μ J of optical trigger energy delivered in 100 ps. A lower limit for the average current density is 170 kA/cm², assuming the current is distributed over the entire cross-section of the PCSS, which is 625 μ m thick. However, it is likely that the current is concentrated near the illuminated surface of the switch, especially near the contact boundaries.

4. PCSS-driven Laser Diode Arrays

High gain GaAs PCSS exhibit three properties which make them ideal switches to pulse LDA. First of all, they are capable of sub-nanosecond turn-on. At high fields, our 1.5 centimeter long switches which can switch over 100 kV, exhibit 350 ps rise times. A second property which makes GaAs PCSS a good choice for LDA pulsers is their high triggering gain. Very little optical energy is required to trigger the switches. The third property is their ability to drive low impedance loads. They are similar to Zener diodes, in that once they are triggered, they exhibit nearly vertical I-V curves offering very little differential resistance. This property was demonstrated with the low impedance fireset application at several kiloamps. LDA require substantially less current, but they are even lower impedance loads than firesets. The resistive impedance of most large arrays is given roughly by R_0/n where n is the number of diodes in the array and R_0 , the resistance of an individual diode being less than 1 Ω .

When we began testing GaAs PCSS as LDA drivers, our goal was to combine a 5 nanosecond, low impedance transmission line, a miniature GaAs PCSS, and a 15 element LDA to produce a 5 ns optical pulse. We were surprised when we discovered sub-nanosecond pulses emerging from the LDA. Apparently, the PCSS was driving the LDA so hard that a significant population inversion was achieved before lasing was initiated. This effect, known as gain switching, is similar to Q-switching, and is observed with individual laser diodes and solid state lasers, when they are pumped with short optical pulses. Our surprise was that this would happen with a whole array of lasers.

Our first report about this result was based on band-width limited diagnostics, with which we estimated pulse widths of 140 ps and peak optical powers of 7 kW. Improved diagnostics have recently provided a better characterization of the electrical and optical properties. A streak camera was used to show that the pulse width from some of the lasers in the LDA is as short as 70 ns (figure 12). These optical streaks were analyzed with an optical profiling camera and software which

produced intensity-time profiles like the example shown in figure 13. Pulse rise times are less than 50 ps. Since our peak power estimate was based on the energy produced in the pulse divided by its area, this shorter pulse width implies higher peak powers. Conservatively, we estimate that the peak power is greater than 10 kW.

Spectral information from the LDA was recorded by filtering the light from a fiber with a monochromator before it was detected with a high speed photo diode (Figure 14). These spectra contain information about the carrier and photon densities which are being reached in the lasers with the sudden injection of charge from the PCSS. When lasers are driven at higher currents, their spectrum naturally shifts to higher energies as higher states in the conduction band are being filled. The interesting thing, shown in these spectra, is that only the initial high speed pulse appears to be broadened to shorter wavelengths.

Figure 12. Streaks from seven lasers in the LDA are shown in this photograph. The bright ones saturate the film, but the four dimmest ones have pulse widths of 65-75 ps and rise times of 40-50 ps. The graticule on the right is in millimeters and the beams are being swept at 16 mm/ns.

Figure 13. Pulse shape obtained from a streak in figure 12.

Figure 14. These diagrams show two views of the time resolved spectral information from a LDA. Each curve was averaged 32 times and the third axis is wavelength in nanometers. The lasers were designed to lase at 904 nm.

Figure 15. A PCSS-driven LDA is used in this complete pulse generator to produce 10 kW, 70 ps wide optical pulses.

A complete PCSS-driven LDA, including power supply, and pulse charger is shown in figure 15. This extremely compact and reliable system only requires a 5 V trigger pulse to generate 10 kW, 70 ps wide optical pulses at 900 nm with sub-nanosecond jitter. This is our first attempt to produce such an optical pulser. Much larger LDA can be driven with GaAs PCSS and further optimization can be achieved. Higher optical powers and pulse energies should be attained in the near future.

Tests with different types of LDAs, are summarized in table II. The key issues are peak power output and pulse width. The table compares values as rated by the manufacturers with our results. Manufacturer data is not available for the extremely short pulse regime where we are interested, because until recently there were no commercial laser diode drivers which could be used to test the LDAs. The single heterostructure, edge emitting lasers gave the best results. They could be driven to gain switching with electrical pulses that were only a few nanoseconds long. At the other extreme were multi-heterostructure, large area lasers which showed signs of reduced efficiency at lower powers, before the gain switching conditions were reached.

Table II. Power achieved from laser diodes with short pulse drivers.

LASER type	number of lasers	rated		tested		power ratio
		power (W)	width (ns)	power (W)	width (ns)	
single heterostructure, broad edge emitting	15 & 20	240	200	10,000	0.14	30
multi-quantum well, MOCVD, edge emit.	637	1000	10	6,600	6	6.6
multi-quantum well, edge emitting	2	20	120	300	2	15
MOCVD, edge emit., central narrow stripe	3	40	200	300	6	7.5
multi-heterostructure, large area, continuous	1	1	cont.	9	50	9

5. Conclusion

Three aspects of high gain GaAs PCSS have been discussed. Data from lifetime tests was reported with our longest lived switching lasting 4×10^6 test pulses. Many factors influence switch lifetime and there are still a lot of potential improvements to be explored. Results from high current switching were described, and improved switching characteristics were achieved with a fiber-optic coupled LDA trigger. Lower switch inductance produced higher current at lower voltage, and the size of the optical trigger energy requirement was reduced by a factor of 200. Optical and electrical properties of PCSS-driven LDA were presented, which show that 75 ps wide, 10 kW pulses can be obtained from a palm-sized optical pulser. PCSS driven LDA are in their preliminary stages of development and should improve dramatically with continued research and development.

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