High Power Light Activated Semiconductor Switches with Sub-nanosecond Rise Times*

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ABSTRACT

This paper presents a summary of results from experiments with large GaAs, InP, and silicon photoconductive semiconductor switches (PCSS). Linear and high gain (lock-on) switching modes will be described. We have used individual PCSS to switch voltages as high as 120 kV and currents as high as 4.2 kA and have produced rise times as fast as 200 ps in the linear mode and 600 ps in the initiation of lock-on. The high gain switching mode is important to applications which must be compact or operate at high repetition rates. The highest power which we have switched to date with a pulsed semiconductor laser diode array (100 W) is 40 MW. The potential development of these switches for future applications will also be discussed.

INTRODUCTION

High power photoconductive semiconductor switches (PCSS) have developed rapidly in the last few years. Properties of low capacitance and inductance, sub-nanosecond rise time and jitter, extremely fast recovery, and optical activation have attracted interest for many applications. Ultra-wideband radar transmitters have a need for high power, fast rise time switches that can be synchronized with sub-nanosecond precision, recover rapidly, and operate reliably for over 10^8 shots. Several groups across the United States are actively developing this field. Communication and cooperation among these groups has advanced development and led to many important observations and discoveries. This paper is an overview of the research and development on silicon and GaAs PCSS at Sandia National Laboratories and does not attempt to summarize the field in general. For a more complete overview of this field, the authors strongly recommend the references.[1-5]

SWITCH CONFIGURATIONS AND CONTACTS

Applications for switches from a few kilovolts to many megavolts have focused our attention on devices which can be scaled up in size to handle higher voltages and currents. The lateral style PCSS that is shown in figure 1 has been pursued particularly for its scalability. The peak voltage that this type of switch can handle is roughly proportional to its length in the direction parallel to the field (40-100 kV/cm). We have fabricated and tested lateral switches of similar design to the one shown in figure 1 with gap lengths ranging from 0.1 to 3.4 cm. Although we have demonstrated that these switches can be operated in series, applications from 1-100 kV regime are possible with single switches.

The contacts that we have used to date are produced with vacuum evaporation and rapid thermal annealing. For silicon we use Cr-Mo-Au, and for GaAs we use Ni-Ge-Au-Ni-Au. Switches with contacts on one or both surfaces have been tested. In most cases, the light which activates the PCSS is absorbed a few microns (532 nm on GaAs) or hundred microns (1064 nm on silicon) from the illuminated surface. However, two-sided contacts facilitate field grading, reduce the field enhancements that occur near the edges of the contacts, and with two-sided illumination allow for potentially twice the current carrying capacity. Switches fired repeatedly at high currents show visible evidence of significant damage to both the metallization and the semiconductor. We are presently pursuing the development of large area ohmic contacts that extend farther into the GaAs and may reduce or eliminate degradation near the contacts.

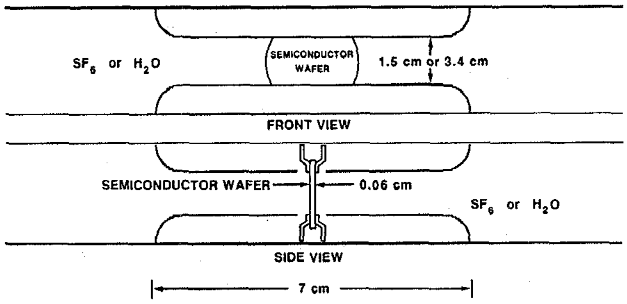

Figure 1. A lateral PCSS configuration is shown in this diagram. Large area contacts are made in four places on this two sided switch. Dark breakdown and switching tests are made with this switch holder which minimizes field enhancements near the planar contacts to the semiconductor.

HIGH PEAK POWER OPERATION

A primary failure mode for lateral PCSS is electrical breakdown across the illuminated surface. We have tested the surface breakdown strength of silicon and GaAs switches without initiating photoconduction. These tests, called dark breakdown tests, give an indication of the ultimate voltage limit of a switch prior to any degradation caused by high current conduction. A silicon switch with a 1.5 cm gap held over 140 kV during 2 μs wide pulse tests under deionized water. Silicon switches must be pulse charged to avoid thermal runaway. Our GaAs switches have reached over 200 kV for 2 μs under water and for 200 ns under SF_6. With DC tests, we have shown that Cr:GaAs switches can hold 30 kV/cm for up to 30 minutes under SF_6. Many techniques (including field shaping, different types of contacts, different dielectric coatings, and surface preparation) have and are being tested to continue to increase the dark breakdown strength of these switches.[6]

The highest hold-off voltages and switched currents which we have reached in switching tests are: 123 kV with 50 Ω and 2.8 kA with 7 Ω using silicon and 115 kV with 50 Ω and 4.2 kA with 1 Ω using GaAs. The voltage waveform from the high voltage silicon test is shown in figure 2. For these tests, switches were triggered once every few minutes

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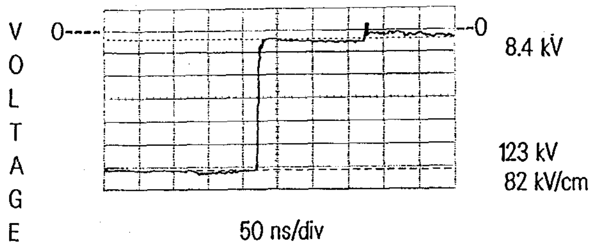

Figure 2. This figure shows the highest voltage switched with a 1.5 cm long silicon PCSS. The switch is triggered after pulse charging to 123 kV.

during gradually increasing voltage pulses, until a surface flash occurred. The values above are those produced during a test prior to destruction. Since switching test results are significantly lower than dark breakdown test results, it is likely that the switches are degrading with every shot, and that improvements in the switches which reduce this degradation will allow their hold-off voltages during switching tests to approach their dark breakdown values.

TRIGGERING REQUIREMENTS

The normal (low field) photoconductive response of a PCSS is the result of the creation of one electron-hole pair per absorbed photon. In nearly intrinsic silicon, the carriers recombine relatively slowly with an exponential decay time of several hundred microseconds. For times short compared to this, a silicon PCSS makes a good closing switch. In GaAs, on the other hand, carriers recombine rapidly with exponential decay times ranging from less than 1 ns in switches with a high defect/impurity concentration to a few microseconds for very pure, defect-free GaAs. Figure 3 shows voltage and current waveforms for a Cr:GaAs switch at low fields. This switch has an exponential recombination time of less than 2 ns, and its response essentially follows the laser shape which was 8 ns wide. For times long compared to its recombination time, a GaAs PCSS makes a good toggling (opening and closing) switch. Neutron irradiation can be used to decrease the recombination time of GaAs making GHz toggling PCSS a possibility.[3]

The "on" resistance obtained with linear PCSS as a function of switch size and optical trigger energy has been calculated previously.[7] Our 1-inch diameter silicon or GaAs switches with 1.5 cm long insulating gaps typically reach less than 5 Ω with a few millijoules of illumination in 5 ns (1064 nm for silicon and 532 nm for GaAs). This relatively inefficient use of optical energy generally restricts the use of PCSS from many large scale applications. Applications for linear PCSS are driven by the need for other switching properties of PCSS such as sub-nanosecond rise times and jitter, megahertz-gigahertz repetition rates, and optical control.

HIGH GAIN SWITCHING: LOCK-ON

At high fields, GaAs exhibits a high gain switching mode which is dramatically different from low field photoconductivity. The light required to trigger GaAs at high fields drops by roughly 3 orders of magnitude. After the optical trigger pulse is gone, if a sufficiently high field remains across the switch, it will continue to conduct instead of recovering its resistance rapidly. Contrast the low field, linear switching waveforms shown in figure 3 with the high field, lock-on switching waveforms shown in figure 4. The trigger pulse widths were 12 ps for both examples. However, at high fields, the switch voltage drops and remains near to a

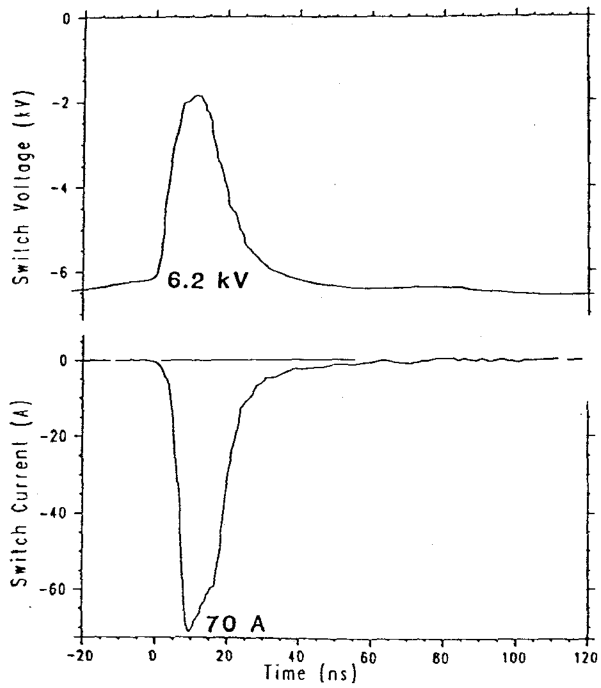

Figure 3. Low field switching with GaAs is shown in this figure. Fast recombination of carriers in the GaAs give a switching response that is comparable to the illuminating laser pulse (12 ps wide).

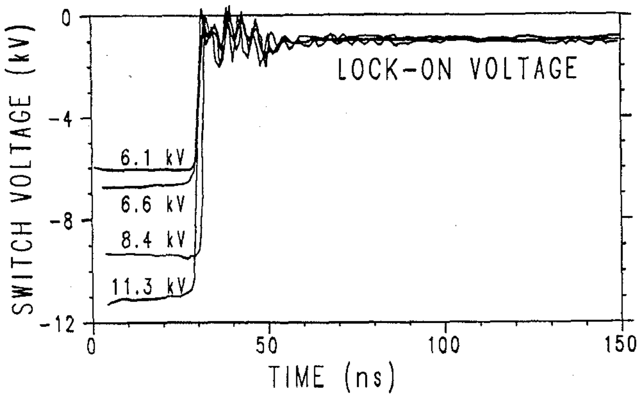

Figure 4. High field switching (lock-on) is shown in this figure. After the laser pulse (similar in shape to the figure 4c) has ended, the switch continues to conduct. The voltage settles to 1 kV independent of the initial charge voltage and switch current.

small but non-zero value. At high fields, a GaAs PCSS is a very efficient closing switch. GaAs switches which required millijoules for reasonable switching at low fields only need a few microjoules to trigger lock-on at high fields. A 1.5 cm long GaAs PCSS was used to switch 40 MW with a 150 W solid state laser diode array. During this test, a 60 ohm antenna was charged to 74 kV and shorted with a PCSS. The rise time was 600 ns.[1] Faster rise times are described in a later section. In the high gain switching mode, this large PCSS can be triggered with a 1 cm^3 laser diode array. However, in the linear mode, a flashlamp pump laser of table-top size would be required.

The properties of the lock-on switching mode have been described in several references.[1-4,8-12] They are summarized here as three phases of switching.

1. Initiation phase: Lock-on is normally initiated when the switch is stressed above an average electric field threshold and illuminated with a short pulse of light. The electrical and optical thresholds to lock-on depend on switch material properties and are inversely related. Figure 5a shows this relation for 1.5 cm long Cr:GaAs switches that were being triggered with a 5 ns long pulse of 532 nm radiation. The electric field threshold ranges from 5-65 kV/cm while the minimum optical trigger energy varies from 800-20 μJ. At high fields, the optical threshold is roughly 1/1000th of that required to produce a comparable photoconductive response at low fields. This effective trigger gain (carriers per absorbed photon) allows the use of much smaller lasers for lock-on switching. The rise time and delay to lock-on which are described in a later section of this paper are too short for carrier injection from the contacts.

2. Sustaining phase: Once lock-on is initiated, the field across the switch will settle to a constant, non-zero value; and conduction will continue even after the optical pulse has ended until the circuit can no longer support this field. This field is called the lock-on field, and, like the threshold field, it depends on material properties of the PCSS. Figure 4 shows the voltage across a GaAs PCSS during lock-on for several different initial voltages. For GaAs, the lock-on field ranges from 3.6-8.5 kV/cm. Tests with one type of InP showed lock-on at 14.4 kV/cm. During this phase, the switch resistance is given by the lock-on voltage drop across the switch divided by the current which is supplied by the circuit. The switch always settles to the same voltage, and its operation is similar to a Zener diode. Tests with circuit impedances ranging from 1-50 Ω justify this analogy and show no other significant contributions to the switch resistance.[4] If carriers were recombining during lock-on in

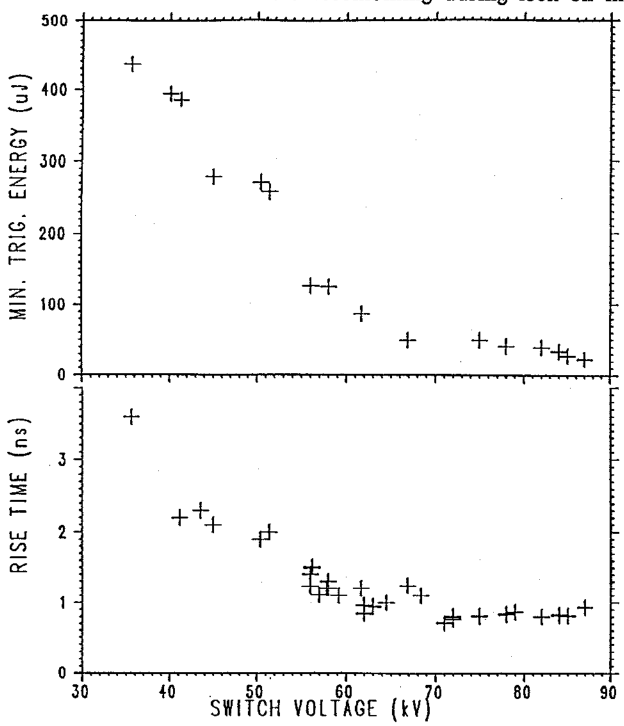

Figure 5. These data show the relations between (a) the minimum trigger energy and (b) switch current rise time as a function of the voltage across a 1.5 cm long GaAs PCSS. The measurements were taken near the thresholds to lock-on and faster rise times are obtain with larger trigger optical energies.

resistance.[4] If carriers were recombining during lock-on in the same way that they recombine at low fields, then the switch would turn off. The fact that the switch continues to conduct also implies gain (effective carriers per absorbed photon) compared to linear photoconductive switching. This gain is proportional to the duration of the sustaining phase.

3. Recovery phase: Lock-on is non-destructive in the sense that the switch resistance recovers to its pretriggered value when the field drops below the lock-on field. If the field returns too rapidly (in either polarity), the switch will go back into the sustaining phase. The shortest time to complete recovery that we have observed for 1.5 cm long Cr:GaAs switches is 35 ns. However, this fast recovery was not obtained consistently. Applications above 5 MHz for low light level triggering of PCSS have drawn our attention to this phase which is discussed in other papers[1,2,4,9]. Lock-on is destructive in the sense that, during repetitive tests, gradual degradation is observed at the contacts. (See a following section on reliability.)

Both the initiation and sustaining phases of lock-on represent gain.[11] Two other characteristics stand-out. Lock-on occurs at fields much lower than one would expect for avalanche breakdown (150-200 kV/cm). It has only been observed with direct band gap semiconductors (GaAs and InP but not Si), which have low mobility satellite valleys in their conduction bands. These characteristics and the need to explain gain have led researchers to suggest impact ionization of impurity/defect levels, the transferred electron (Gunn) effect, ultra-fast thermal runaway, and double injection as potential explanations for lock-on. This paper does not attempt to discuss the models for lock-on switching, but refers the reader to the literature.[1-4,12,13] A single satisfactory explanation which incorporates all the properties of lock-on has not yet been published.

RISE TIMES

In the linear mode, the switch resistance as a function of time is proportional to the time integral of the optical intensity convoluted with exponential carrier recombination.[7] Thus the rise time of the switch is determined by the width of the activating light pulse and the semiconductor carrier recombination time. With silicon, we have measured 270 ps rise times using 100 kV size switches. With GaAs, lock-on may be an issue. Whether or not a GaAs PCSS is above the electric field threshold to lock-on, sufficient optical trigger energy can be applied to obtain a linear photoconductive response that will determine the switching rise time. Figure 6 shows a 200 ps rise time obtained from a switch at fields above and below lock-on. In both cases, the laser was sufficiently intense to initiate linear switching. When triggering lock-on at low light levels, however, the rise time of the switch is a strong function of the initial voltage across the switch. This dependence is shown in figure 5b. These rise times were obtained using an 8 ns wide laser pulses with energies just above the optical threshold to lock-on at each voltage tested. In contrast to linear switching, the rise times obtained with lock-on are not a strong function of the optical pulse shape.

Switches operating near the electrical and optical thresholds to lock-on show a significant delay from when they receive the optical trigger to lock-on switching. This delay approaches zero (+/- 1 ns) as the field across the switch is increased as shown in figure 7. Such delays could lead to jitter in systems with multiple PCSS switches which are operating near the thresholds to lock-on. Even at high fields, jitter may be significant for sub-nanosecond applications. The width and shape of the optical trigger pulse may be important for low jitter applications of lock-on.

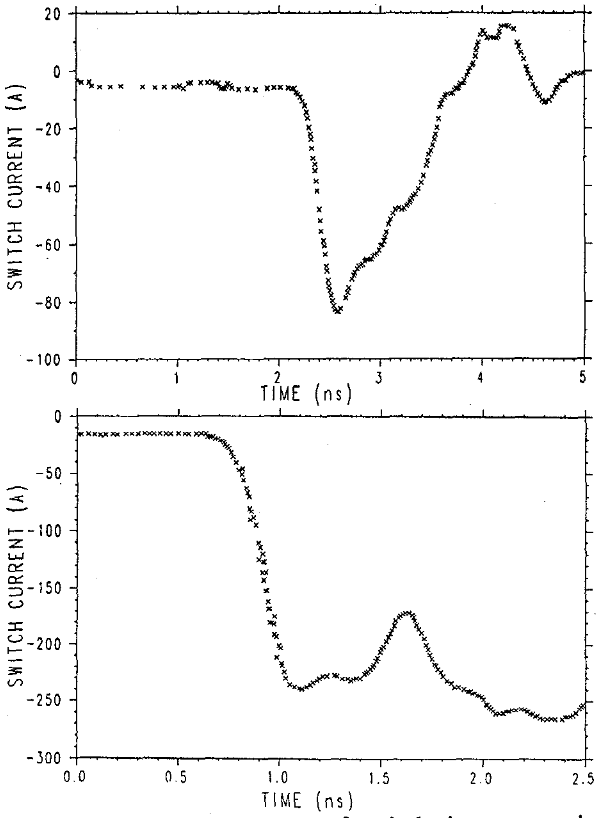

Figure 6. Approximately 20 mJ of optical trigger energy in a 200 pd wide pulse was used to obtain the rise times shown above and below the threshold to lock-on. Below lock-on (top curve), fast carrier recombination leads to current turn-off in 1 ns. At higher voltages (bottom curve), the switch continues to conduct.

REPETITIVE OPERATION AND RELIABILITY

We have demonstrated 40 MHz, short burst operation of GaAs PCSS below the lock-on field.[9] Large laser energy requirements make this type of high frequency operation impractical for most high power applications. Above 5 MHz, lock-on switching demands extremely fast recovery and is presently being pursued[1,2,4,9]. Using the lock-on mode at lower frequencies, allows reliable repetitive triggering with laser diode arrays. We have operated small (2.5 mm long) GaAs PCSS at 1 kHz, 1 MW for 10^5 shots. At this point there is significant erosion of the contacts and damage to the GaAs near the contacts which leads to surface flashover and destruction of the switch. We are presently developing better contacts with the goal of reducing this damage and increasing the reliability of these switches.[1,2]

CONCLUSION

The switching properties of PCSS are being developed for high power applications for extremely short pulses and high frequencies. We have operated 100 kV size PCSS with rise times as short as 200 ps, delivered 40 MW to 30 Ω and 4 kA through 1 Ω using laser diode arrays, and tested small switches at 1 MW for 10^5 shots. These switches can be operated in either a linear or high gain switching mode. Issues demanding further research and development are: rise time, jitter, and fast recovery in the high gain mode and improved contact development for higher currents and greater reliability.

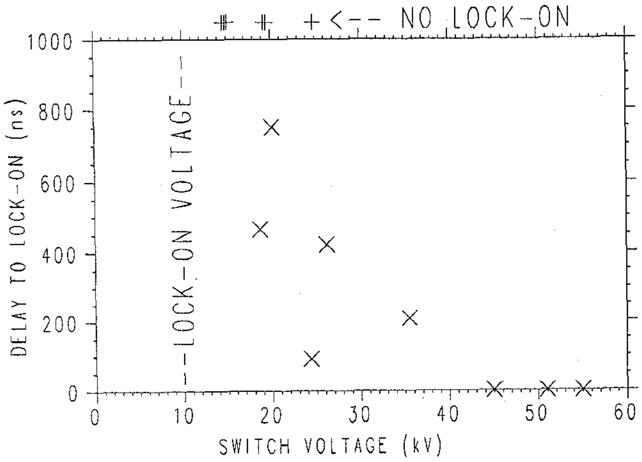

Figure 7. The delay between the photo-response from low light level triggering to eventual lock-on switching is plotted here as a function of the voltage across a 1.5 cm long GaAs PCSS. The delay goes to zero (with a 1 ns resolution) as the field across the switch increases. This switch was charged with 2 μs wide pulses. Tests which did not go into lock-on may not have had enough time and are therefore plotted above the scale at their respective voltages.

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