PROPERTIES OF HIGH GAIN GaAs SWITCHES FOR PULSED POWER APPLICATIONS*

Fred J Zutavern, Guillermo M. Loubriel, Harold P. Hjalmarson, Alan Mar,
Wesley D. Helgeson, Martin W. O'Malley, Mitchell H. Ruebush
Sandia National Laboratories, Albuquerque, NM 87185-1153
(505)845-9128

R. Aaron Falk, OptoMetrix, Inc., Renton, WA 98058
(206) 271-0779

Abstract

High gain GaAs photoconductive semiconductor switches (PCSS) are being used in a variety of electrical and optical short pulse applications. The highest power application, which we are developing, is a compact, repetitive, short pulse linear induction accelerator. The array of PCSS, which drive the accelerator, will switch 75 kA and 250 kV in 30 ns long pulses at 50 Hz. The accelerator will produce a 700 kV, 7kA electron beam for industrial and military applications. In the low power regime, these switches are being used to switch 400 A and 5 kV to drive laser diode arrays which produce 100 ps optical pulses. These short optical pulses are for military and commercial applications in optical and electrical range sensing, 3D laser radar, and high speed imaging. Both types of these applications demand a better understanding of the switch properties to increase switch lifetime, reduce jitter, optimize optical triggering, and improve overall switch performance. These applications and experiments on the fundamental behavior of high gain GaAs switches will be discussed. Open shutter, infra-red images and time-resolved Schlieren images of the current filaments, which form during high gain switching, will be presented. Results from optical triggering experiments to produce multiple, diffuse filaments for high current repetitive switching will be described.

Introduction

The first half of this paper discusses several high speed switching applications that can benefit from some of the advantageous properties of high gain GaAs photoconductive semiconductor switching (PCSS). These applications are: (1) compact, repetitive particle beam accelerators; (2) ground penetrating radar (GPR); (3) optically activated electrical firesets; (4) semiconductor laser diode drivers; (5) electro-optic (Pockels cell) drivers; and (6) high voltage triggers for gas discharge switches. For each application, we briefly describe the purpose, switching goals, benefits from using PCSS, and issues or areas which require improved PCSS operation. From these descriptions, one can see that both benefits and issues depend on the specific application. Additional information on some of these applications can be found in the literature[1]. The second half of the paper reports experiments and calculations that are focused on understanding and improving these switches. Many of the present limitations of high gain GaAs PCSS are being eliminated or reduced by learning more about switch operation, fabricating switches with different types of

Table I. Switching results achieved with high gain GaAs PCSS (not simultaneous).

maximum power	60 MW
maximum voltage	155 kV
maximum current	7 kA
minimum trigger energy	2 nJ
maximum trigger gain	10^5
maximum electric field	100 kV/cm
minimum rise time	350 ps
minimum r-m-s jitter	80 ps
max. continuous rep. rate	1 kHz
max. burst rep. rate	5 MHz
max. device lifetime	25,000,000

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electrical contacts, and testing switches in different configurations. A list of switching properties, which we have demonstrated with high gain GaAs PCSS is shown in Table I. A key issue for almost all PCSS applications is device longevity. Most of our research and development in this area is not described in this paper, because it is covered in a companion paper that is devoted to PCSS longevity.[2]

Applications

Compact, repetitive, short pulse, particle beam accelerators can be used as radiation sources for radiography, materials processing and sterilization of food, medical equipment, and medical waste. They could also be used in biological counter-proliferation to sterilize suspicious packages at the site of discovery. An entry point in these areas is a PCSS driven linear induction accelerator[3], that we are developing to produce 700 kV and 7 kA in 10-30 ns long pulses at 50 Hz. The benefits of using high gain PCSS over conventional spark gap based accelerator technology are: size, weight, repetition rate, rise time, and jitter. The issues are switch lifetime, switched current, and stand-off voltage. Continuous operation at 50 Hz or higher requires switches that will last for 10^7 or more pulses per 40 hour week. Although some of the uses described here would not require continuous operation, the general need for long-lived switches is clear. Switch degradation is exacerbated by the requirements for high currents. Our linear induction accelerator is a modular voltage-adder that requires 56 kA through the switches or 28 kA and 200 kV into the induction cavities to accelerate 7 kA at 700 kV. Our approach to build a PCSS based accelerator with reasonable lifetime (10^7 pulses) has been to limit the current per filament in the PCSS to less than 50 A by initiating many filaments in each GaAs wafer. We have used line triggering to produce 30 current filaments across a 3 cm wide GaAs PCSS (Figure 1). We are presently testing a 6 wafer module which will power $1/8^{th}$ of the accelerator. Fiber optics are being used to deliver the optical trigger to the switches and 1 mm diameter glass rods are being used to focus the light into 100-200 μm wide lines across the active region of the switches. With this design, the full accelerator will be powered with 48 wafers which conduct current in 1440 filaments, or 39 A per filament. More information on line triggering is provided later in this paper under the section on triggering experiments. PCSS lifetime improvements and testing are described in the companion paper[2].

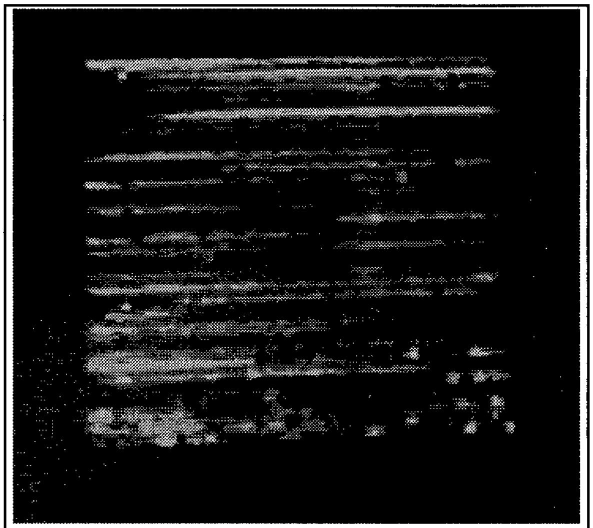

Figure 1. Thirty filaments across a 3.4 cm long by 3 cm wide GaAs PCSS. The filaments are triggered and viewed through a layer of 1mm dia. glass rods above the GaAs wafer. In this test the switch was charged to 60 kV and conducted 380 A.

Ground penetrating radar detects underground objects with wide-band RF impulse radiation. Switching goals are 100 kV, 1-2 kA for 3 ns at 1-1000 Hz. The benefits of PCSS are high peak power, fast rise time, compact size, and small jitter. Issues are lifetime and post-pulse noise. We have demonstrated the ability of GaAs switches to create voltage pulses suitable for driving ultra wideband (UWB) transmitters[4,5]. In that test we charged a nominally 3.0 ns long, 50 Ω, parallel plate transmission line to voltages of about 100 kV. This line was discharged with either one or two switches into a 50 Ω load or a TEM horn antenna. The radiated pulse and reflections from a different targets have been measured. Ground penetrating tests will commence in October, 1997.

Firing sets are used to initiate conventional and nuclear explosives. They consist of a power supply, high voltage capacitor, high voltage switch, and a resistive detonator. Switching goals are 1-5 kA at 1-5 kV for 50 ns, with 100 pulse lifetime for testing. The system requirements on the high voltage switch demand precise timing, small volume, high voltage, high current, and very low inductance to produce fast current rise times with a sub-Ohm load. PCSS are being developed to replace present switch technology because of their extremely fast switching and small physical volume. We have tested a system[6] that consists of a 120 nF ceramic capacitor which is discharged through the switch into a 0.25 Ω load. The capacitor is either DC or pulse charged to 3 kV. When triggered, the switch current has a rise time of <30 ns with a peak current of 3 kA. Issues are the on-state voltage loss and device lifetime.

Laser diode drivers are used to generate high peak power optical pulses by injecting short, high current pulses into semiconductor laser junctions. If the peak current is high enough and the pulse rise time is sufficiently short, the semiconductor lasers will achieve a substantial population inversion before lasing initiates. This sudden increase in laser gain, called gain switching, produces sub-nanosecond optical pulses with optical peak powers that depend on the size and type of semiconductor laser diodes. These optical pulses are used in research laboratories and for military and industrial applications such as active optical sensors for optical range sensing, 3D laser radar, and high speed range-gated imaging. We have demonstrated 100 nJ in 75 ps (1.3 kW) from individual, single heterojunction, edge-emitting lasers[3,7]. We have used PCSS to drive arrays of 20, 100, and 600 lasers with total pulse energies of 2, 12, and 48 μJ, respectively. PCSS switching goals are 200-1000 A at 1-15 kV depending of the size and electrical configuration of the laser diode arrays (LDA). The effective impedance of each individual laser is less than 1 Ω, so parallel configurations, which are the standard monolithic configuration, can be extremely low impedance. In the low impedance (R) regime, the rise time of any driving circuit is usually dominated by the circuit inductance (L) and is given by L/R. The benefits of using PCSS for this application are its low inductance, rise time, peak currents, repetition rate. Primary issues for this applications are device lifetime and jitter.

Electro-optic (Pockels cell) drivers are used for electrically-driven optical switching. Such devices are used in lasers for Q-switches, cavity dumpers, pulse selectors, and regenerative amplifiers. Switching goals are 1-8 kV in 50 Ω systems, sub-nanosecond rise times and in some cases kHz or even MHz repetition rates. The benefits of PCSS are rise time, optical activation, compact size, and low cost. Issues are switch lifetime and jitter for precise synchronization with other systems. We have used PCSS to deliver up to 5 kV to Pockels cells and demonstrated optical rise times of less than 600 ps[6].

High voltage triggers for gas discharge switches. The switching goals are 50 kV, 50 Ω, and high repetition rates. Benefits of using PCSS are optical activation, compact size and cost. Issues are jitter and device lifetime. We have demonstrated 80 ps and 350 ps rise time with PCSS, and are presently assembling a system to trigger high voltage gas discharge switches with a PCSS.

PCSS Triggering Experiments

A vertical cavity surface emitting laser (VCSEL) has been used to trigger a 1 mm long GaAs PCSS. As shown in Figure 2 below, this VCSEL emits 2.15 nJ of energy. The peak power of 80 mW may be underestimated due to the limited bandwidth of the photodetector and oscilloscope used to obtain the measurement. The laser has a “hollow” square emitting aperture of 75 μm width, with a lasing wavelength of 850 nm, and is optimized for high output efficiency. A high numerical aperture, aspherical lens was used to image the VCSEL output onto the surface of the switch with nominally unity magnification. The switch was biased at 3.5 kV, resulting in a current pulse of 43 A upon triggering. The integration of high-gain PCSS with trigger lasers has important implications for many applications in terms of manufacturability, reliability, cost, and packaging. VCSELs may play an important role in the implementation of such a device due to their advantages of surface normal emission and ease of array fabrication and on-wafer testing. VCSEL arrays may also eventually be used to initiate multiple filaments. An outstanding issue for VCSEL triggering of PCSS devices has been that of the optical pulse energy required to cause the switch triggering. Previously, the minimum energy that had been observed to achieve switch firing was 13.6 nJ in a 40 μm diameter spot of illumination, at a wavelength of 532 nm.

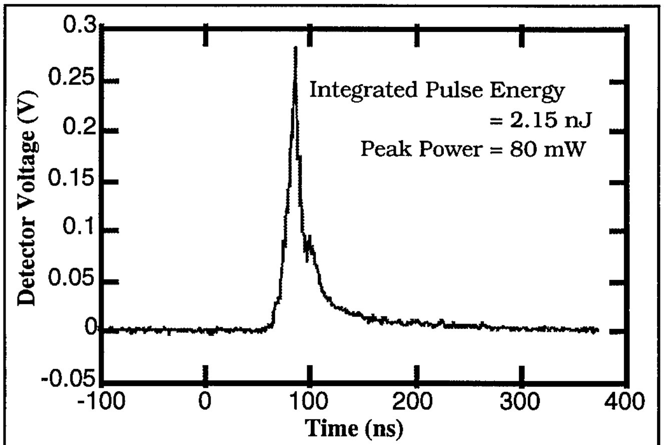

Figure 2. The optical output from a VCSEL which was used to trigger a 1 mm long GaAs PCSS.

The energy to required to trigger a high gain GaAs PCSS is minimized by focusing it to a point near one of the contacts, where the initial field is apparently highest. However, to initiate multiple filaments on a single wafer, additional optical energy is expended with line-triggering to precisely control the location of the filament. Multiple filaments reduce the switch inductance and increase the total current carrying capacity of the PCSS, as switch longevity is limited by contact damage which depends on the current per filament[2]. PCSS line-triggering experiments have produced thirty filaments on a single GaAs wafer (Figure 1). The trigger pulses were transported to the switch in thirty-two 200 μm diameter fibers (0.21 NA). The average optical energy per fiber was 15 μJ of 532 nm light. The light from the fibers was focused into lines with a layer of 1 mm diameter glass rods placed directly on the surface of the PCSS. The fibers were grouped into a line of 8 bundles separated by 2mm and 18 cm above the glass rods. The switch and glass rods were submerged in Fluorinert to inhibit electrical breakdown near the surface of the switch. Figure 1 shows a variation in the intensity along the individual filament lines. Part of this variation is caused by viewing the image of the filaments through the layer of glass rods. If the filaments do not form directly below the rods with respect to the camera, their emitted light is not directed toward the camera. Another contribution to the variation is that in some regions the filaments are formed deeper in the GaAs and more of the emission is re-adsorbed by the GaAs.

The jitter, or variation in the delay between the optical trigger pulse and the onset of switching, was measured in a 1 mm long GaAs PCSS charged to 4 kV. It was triggered with a single laser diode modified for fast rise time with approximately 1/2 μJ of 880 nm light. A 4 GHz transient digitizer and high speed PCSS circuit was used to make this measurement. The trigger pulses were delivered through a 300 μm diameter fiber optic placed near the surface of the switch. Ninety-six successive current waveforms were recorded. The root-mean-square variation was 80 ps and the first-to-last spread was 390 ps. There has been some indication that line triggering may reduce the jitter further by eliminating some of the statistical variation in filament formation. We plan to repeat this experiment with line triggering.

PCSS Imaging Experiments

Time-resolved images of current filaments (Figure 3) were obtained using a Schlieren imaging technique[8]. The technique images small changes in the refractive index of a the semiconductor substrate due to current density and temperature. In this experiment, one LDA was used to trigger the PCSS with 850-880 nm radiation which is strongly absorbed in GaAs. Another LDA is used to illuminate switch with 904 nm which is only weakly absorbed in GaAs. Images of the refractive index variations during the second pulse are captured with a CCD camera. Time resolution is obtained by using short optical pulses varying the delay between them. In Figure 3, the trigger pulse and the imaging pulse were 13 ns wide. Our original results were obtained with 300 ps pulses from an ND:YAG laser. The coherence length of that laser produced speckle patterns which seriously degraded the images. Using an LDA eliminated speckle. In our next experiments, we plan to improve time resolution and magnification.

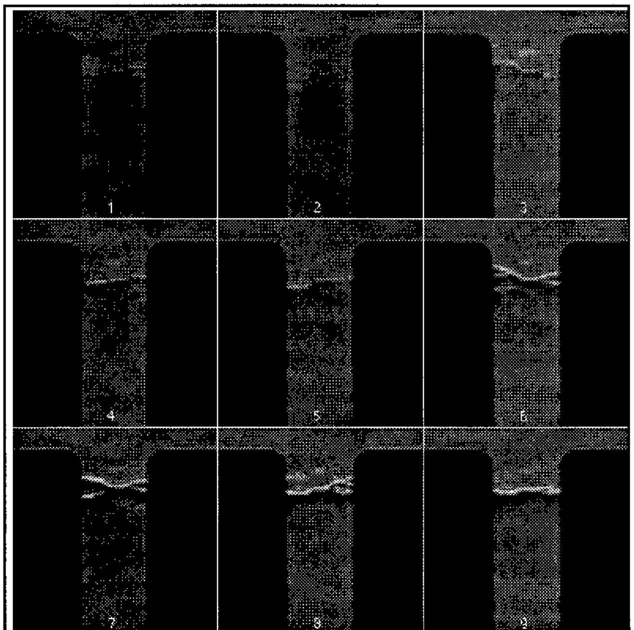

Figure 3. Time resolved images of current filaments obtained with a Schlieren imaging system. These photos show images of current density and temperature obtained from independent switching events where the delay between the optical trigger pulse and the Schlieren probe pulse increases by 5 ns with each frame from 0-40 ns.

High Gain PCSS Modeling

Theory predicts that semi-insulating (SI) GaAs can exhibit bistable switching. Normally, SI GaAs has a highly resistive OFF state[9]. Under the right conditions it can be optically triggered into a highly conductive ON state in which the current flows in filaments. The mechanism for this process is collective impact ionization which occurs at high carrier density when carrier-carrier scattering is faster than carrier-phonon scattering. In this limit, an electric field (5 kV/cm) is able to sustain a stable filament by impact ionization. Figure 4 shows a series of plots of electron and hole carrier density as a function of time in a 100 μm switch. The contacts have dopant concentrations of 10^{18} cm^{-3} and thicknesses of 10 μm. An initial 1 ps excitation pulse of Gaussian profile generates a neutral plasma of electrons and holes. The logarithmic time scale has 5 steps per decade. A forward bias (100 V) causes electrons to begin impact ionization at both the n-contact (left) and the right-hand-side of the plasma. For each electron, a hole is generated and it flows to the left. At the end of the 1 ns calculation, the filament carrier density is nearly uniform except near the contacts. At the n-contact, the holes "pile-up" which leads to increased electron injection. The net result is a reduced electric field and carrier temperature in the contact. A similar phenomenon occurs in the p-contact due to "pile-up" of the electrons. This model is now being used to improve switch lifetime and predict the performance of the switches.

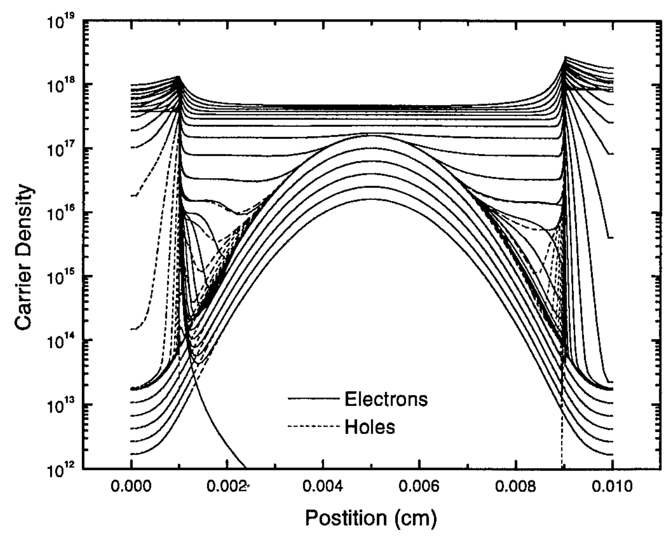

Figure 4. This 1-d transport calculation is capable of showing the effect excitation conditions, circuit conditions, doping, and switch geometry on the switch voltage, current, rise time, and temperature.

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