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PCSS LIFETIME TESTING FOR PULSED POWER APPLICATIONS *

T. A. Saiz, F. J. Zutavern$^{\xi}$, S. F. Glover, K. W. Reed,
M. J. Cich, A. Mar, M. E. Swalby, M. L. Horry
Sandia National Laboratories, Albuquerque, NM 87185 USA

Abstract

Trigger systems are becoming increasingly important in pulsed power systems with large numbers of high voltage switches (HVSs) or large numbers of different switching times. Performance can be critical with demands for fast rise-times, sub-nanosecond jitter, and long lifetimes. In particular component lifetimes affect maintenance costs and the available operational time of the system. High gain photoconductive semiconductor switches (PCSSs) deliver many of the desired properties including optical-isolation, 350 ps risetime, 100 ps rms jitter, scalability to high power (220 kV and 8 kA demonstrated), and device lifetimes up to 10^8 shots with 21 A per filament in 5 ns wide pulses [1**Error! Reference source not found.**], [2**Error! Reference source not found.**]. However, higher current and longer pulse applications can drastically reduce device lifetime. For typical single shot pulsed power applications, lifetimes of several thousand shots are required and much longer-lived HVSs are required for repetitive pulsed power applications.

The key parameters that impact PCSS lifetime are voltage, current, and pulse width. Voltage affects the lifetime of a lateral switch when the electric field near the surface of the switch approaches the surface breakdown limit, which is approximately 100 kV/cm for sub-millimeter pulse charged PCSSs (→70 kV/cm for larger ones) under transformer oil or Fluorinert (a liquid dielectric). The current in high-gain GaAs PCSS always forms filaments, so this lifetime dependence can be considered in terms of the current per filament, and most of our lifetime testing is done with PCSS producing a single main filament. Since PCSS can have sub-nanosecond risetime and jitter, most of our interest in lifetime is for switches that produce 1-100 ns long pulses. These requirements lead us to testing high gain PCSS in high speed, 50 ohm transmission line, discharge circuits that can deliver up to 300 A. Control of the PCSS is achieved with a fiber-coupled laser directed between the PCSS metal contact pads resulting in one randomly formed primary filament.

Devices demonstrating long lifetimes are operated at up to a few kilohertz, whereas higher current and longer pulse tests are operated at lower repetition rates. In all cases, rep-rates are below the limit where bubbles or particles form in the liquid dielectric. New PCSSs are always tested at 20 A for direct comparison to the lifetime data that we have accumulated over the last 20 years. Higher current tests are performed to predict switch lifetimes for specific applications that don't require such long device lifetimes. This paper will discuss testing procedures, circuits, and dramatic changes in PCSS component lifetime due to contact methods (e.g. soldering versus ribbon bonding).

I. INTRODUCTION

Existing high voltage electrical trigger generators (TGs) for HVS will present significant cost and implementation tradeoffs as pulsed power designs are scaled to accommodate large numbers of HVS [3] and sequential switching capabilities [4]. The model fusion driver [3] combines currents from 504,000 switches. Assuming 20 HVS can be triggered per TG, this results in a requirement for a trigger system that will cost $630 million at $25 K per TG. To keep the output power of the fusion system sustainable a shot rate of 0.1 Hz is being targeted [5]. At this shot rate the lifetime sought for the HVSs and TGs in this system is 10^7.

A proposed compact driver for isentropic compression has 236 independent HVS. Current ripple requirements force a minimum of 59 independent TGs, which with commercial electrical TGs would comprise a third of the system cost. Greater savings and performance is anticipated with PCSS based TGs that also yield significant simplification by using fibers to replace high voltage trigger cables and line-of-sight optics.

PCSSs deliver many desired properties **Error! Reference source not found.**] and are used in a variety of pulsed power applications. They offer improvements for existing and future pulsed power systems. They are being tested for use in high impedance, low current applications, as well as high voltage, high current applications. This paper focuses on improved PCSS lifetime for high performance, reliable, cost effective PCSS based trigger generators [6], Fabrication of PCSS and the processes that impact PCSS lifetime are described in another paper at this conference [7].

II. PCSS STRUCTURE

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$^{\xi}$ email: fjzutav@sandia.gov

PCSSs for this project are made from a rectangular piece of bulk GaAs. P-metal is deposited onto the surface of one end of the GaAs piece and n-metal on the other. Gold bonding metal is then deposited on to the surface of the pads. Due to photolithographic limitations, the edge of the bond metal cannot be lined up perfectly with the metal pad. To guarantee that the edge of the bonding metal does not overlap the surface of the raw GaAs, the edge of the bond metal is placed a few microns from the edge of the metal pad. This is referred to as the bond-metal inset. See Figure 1. For a more detailed explanation of the surface layers please refer to [7].

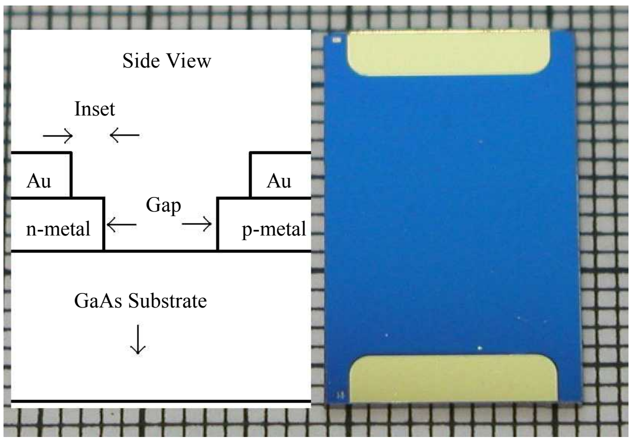

Figure 1. Left: surface layer diagram. Right: SiN coated GaAs PCSS-15 mm.

Devices for this research are fabricated with vapor deposited metal layers that are sintered with rapid thermal annealing. This is a less expensive process than the process that has produced the best results, but it can produce devices with lifetimes greater than 10^6 shots at 20 A peak current/filament. This is sufficient for most pulsed power applications. If lifetimes of 10^8 shots are necessary, then epitaxial re-growth can be used, but it is a more expensive and time consuming process.

III. TEST CIRCUIT

The test-bed used for the results presented here is set up in an automated configuration, Figure 2, capable of charging the PCSS up to 20kV and firing greater than 10^7 shots without operator interaction. To facilitate high bandwidth pulse formation and diagnostics, the PCSS is mounted between two sections of a 50 Ω high voltage transmission line: a 15 cm long charged section that is switched into a 152 cm long section which terminates into a 50 Ω load and a current viewing resistor (CVR). The PCSS is positioned in a flourinert (a dielectric liquid) filled gap created in the inner conductor of the HV cable, as pictured in Figure 3.

Pulse charging is accomplished using a capacitive ring up circuit which connects to the 15cm, 15pF section of HV cable through a diode stack, as indicated in Figure 4. This configuration provides a 680ns risetime charge pulse.

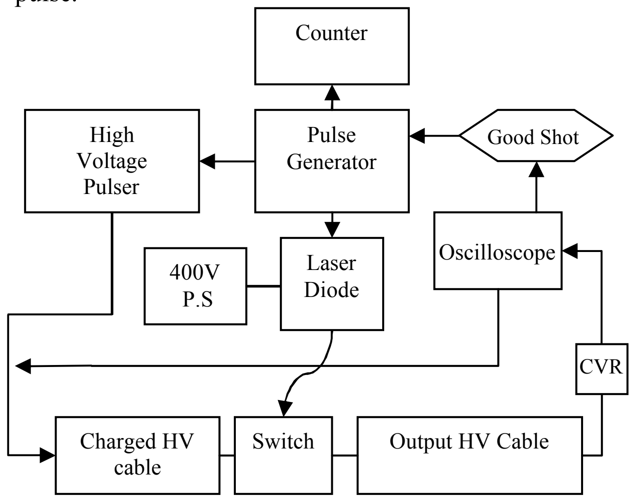

Figure 2. Block diagram of the lifetime testbed.

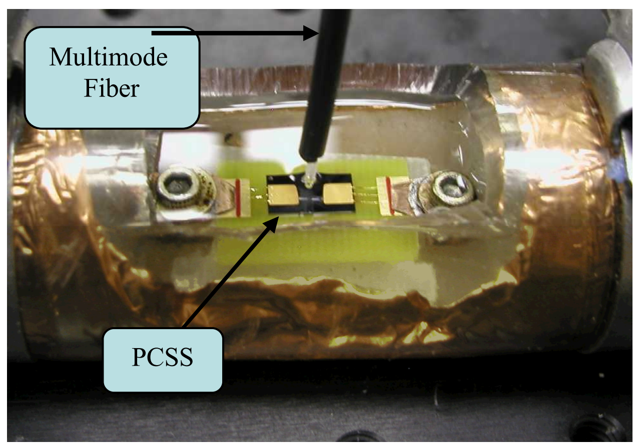

Figure 3. A 2.5 mm, wire bonded PCSS positioned between inner conductors of an RG220 high voltage cable.

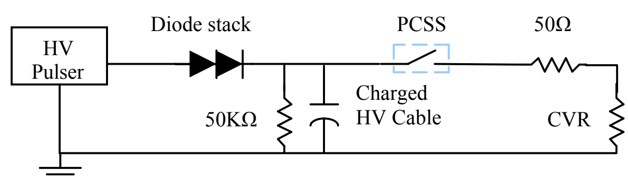

Figure 4. Test circuit diagram.

Triggering of the PCSS is synchronized with the charge pulse using a Stanford DG535 delay generator to ensure a consistent charge voltage for each shot. The laser driver receives a trigger command from the pulse generator, Figure 2, and activates the laser diode generating a 15 ns 850 nm pulse with 2-3 μJ of energy. An optical fiber transports the laser diode output to the PCSS, as seen in Figure 3, creating a spot on the surface of the PCSS between the two metal pads. Alignment of the spot on the PCSS is critical, because the photons from the laser initiate avalanche carrier generation (high gain) [6]. Therefore alignment affects the location of the filament, the consistency of triggering, and jitter.

Closing the PCSS delivers a 2.5 ns pulse to the output HV cable and the CVR. A TD53032B Tektronix oscilloscope and a Canberra 2072A digital dual counter monitor the output pulses. If the pulse current exceeds a preset threshold the PCSS is considered operational and the oscilloscope provides a command signal to initiate the next cycle.

IV. LIFETIME TESTING

Switch design parameters that are expected to affect the switch lifetime include: material type, fabrication method (as mentioned in section II), bond pad inset, bonding metal thickness, annealing temperature, circuit attachment method, and coatings. For our discussion circuit attachment method refers to soldering versus wire bonding. For a more detailed discussion on these parameters please see.[7].

Soldering directly to the PCSS is one method for attaching a PCSS to a circuit. In this set up copper strips, cut to be the same width as the bond pads, were attached using indium solder, see Figure 5. However, microscopic photos, Figure 6, of the PCSS before and after soldering indicate that bits of solder sputter on to the GaAs surface between the metal bond-pads. This sputtering and the elevated temperature may affect the lifetime of the device.

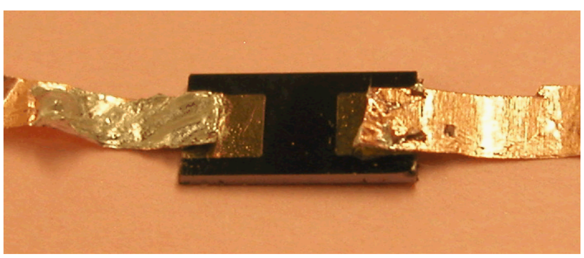

Figure 5. Soldered switch with 2.5 mm gap spacing

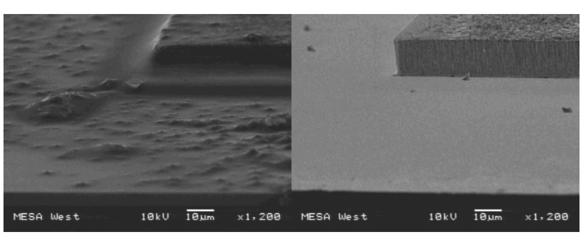

Figure 6. PCSS surface with soldering (left) and without soldering (right).

Wire bonding can be used to eliminate unwanted solder sputter and temperature elevation by making clean, cold connections to the PCSS. Figure 7 contains a picture of a wire bonded PCSS. In this picture the PCSS is setting on top of a rectangular piece of printed circuit board (PCB) and wire bonds have been installed to connect between the pads on the PCB and the pads on the PCSS. The PCSS and PCB are then inserted into a circuit as an assembly. Soldering can now be used on the PCB (at a distance from the PCSS). Solder mask is placed on the PCB pads to prevent flow to the bonded wires.

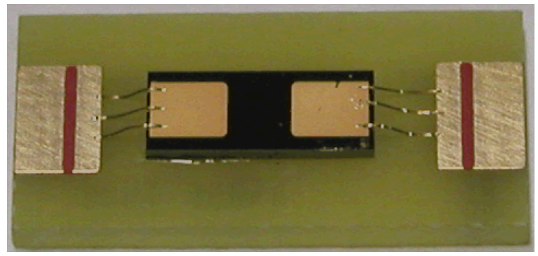

Figure 7. Wire bonded switch with 2.5 mm gap spacing.

Bond pad inset (defined in section II) impacts field enhancement and the amount of current a switch can handle. A smaller inset produces less field enhancement and allows the switch to handle higher currents, but is limited by fabrication procedures during the alignment process. Insufficient inset allows the filaments to bypass the sintered metal layers resulting in greater damage to the GaAs.

Bond pad thickness should be sufficient to avoid damage to the bond pad from the total current. For our samples electron beam metal evaporation was used for the 1um thickness, while electro-plating was used for the 11um thickness.

Annealing temperature affects adhesion of the bonding metal to the GaAs. Higher annealing temperatures result in better adhesion. However it also results in higher field enhancements due to increased non-uniformity of the contact pads.

AR coating on the surface of GaAs is used to reduce laser light reflection and is used to protect the GaAs surface. Use of an AR coating is standard practice in low field applications, but the coating may degrade under high field operation.

A. Initial Results

Of the many factors that can influence PCSS lifetime we are presenting results from variations in the annealing temperature, bond metal thickness, bond pad inset, and AR coatings. All PCSS were soldered for these tests. Evaluating wire bonded devices was in progress at the time of this writing.

For evaluation purposes lifetime testing has been conducted at 20 A per filament which allows for direct comparison to results from the previous 20 years of testing [8]. Test preparation starts with insertion of the PCSS and then triggering the PCSS at a rate of 1Hz. During this time the position of the optical fiber is adjusted until the spot size fills the gap between the bond pads and a single filament is easily and consistently formed. The trigger rate is then increased to 20 Hz and the PCSS is cycled until filaments no longer consistently form.

Initial results from this latest series of tests are listed in Table 1. Lifetime variations of up to two orders in magnitude have been measured with the parameter variations listed. Notice the least expected change in lifetime occurred with the removal of the AR coating which resulted in an order of magnitude longer life than the devices with the coating. Removal of this coating was requested after evidence of AR coating damage prior to the failure of the PCSS had been noticed. Further testing is necessary to determine if it is the coating that reduces lifetime or if it is the process of adding and removing the coating that increases the lifetime.

Testing of new devices is not complete. Further testing with wire bonding and PCSS cut from the wafers listed in Table 2 is in progress.

Table 1. Initial lifetime testing results

Switch Name	Anneal.temp for 1 min (C)	Bond metal thickness[1] (μm)	Bond pad Inset (μm)	AR coating	Lifetime # of shots
002XT-1	420	1	5	yes	198,538
002XT-2	420	1	5	yes	51,910
002XT-3	420	1	5	yes	67,646
002XT-4	420	1	5	yes	53,751
056XT-1	420	1	5	removed	555,061
056XT-2	420	1	5	removed	605,900
056XT-3	420	1	5	removed	1,907,774
067XT-1	430	11	1	no	7,712
067XT-2	430	11	1	no	7,160
067XT-3	430	11	1	no	7,697

[1] Note that 1μm thicknesses were applied with electron beam metal evaporation and 11μm thicknesses were applied with electroplating.

Table 2. New wafer parameters

Wafer name	Anneal.temp for 1 min (C)	Bond metal thickness[1] (μm)	Bond pad Inset (μm)	AR coating
003XT	420	1	5	yes
061XT	420	1	5	no
063XT	430	1	1	no
064XT	430	1	1	no
066XT	430	11	1	no

[1] Note that 1μm thicknesses were applied with electron beam metal evaporation and 11μm thicknesses were applied with electroplating.

V. CONCLUSION

Testing described in this paper is part of a continued effort to develop PCSS for high voltage switch trigger generation and other pulsed power applications. Initial test results indicate that lifetime can be improved by orders of magnitude by careful control and selection of the manufacturing process. Further testing with PCSS investigating the affects of annealing temperature, bond metal thickness, bond pad inset, AR coatings, and soldering versus wire bonding is in progress.

VI. REFERENCES

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