INVESTIGATION OF CRYOGENIC PHOTOCONDUCTIVE POWER SWITCHES*

Roy M. Goeller, M. Clark Thompson, Robert B. Hammond, and Ross A. Lemons
Los Alamos National Laboratory
Los Alamos, NM 87545
(505) 667-0902

William Nunnally
University of Texas at Arlington

Abstract

Repetitive photoconductive power switching with a Nd:Yag laser at pulse rates up to 100 Hz was demonstrated at room and cryogenic temperatures. A silicon rod 3 cm in length and 9 mm in diameter with a resistivity of 1 Kohm-cm was optically triggered in a circuit capable of allowing us to pulse charge the system or to bias the switch with constant voltage. In the pulse charge mode, an HY8 thyratron was used as a series switch to place a maximum of 1.25 J of stored energy in a 0.1 uf capacitor. This energy was then delivered to a 0.5 ohm load by optically triggering the photoconductive switch. In the direct current mode of operation, the triggering was performed with a constant voltage across the switch and load combination. These two arrangements made it possible to study the effect of thermal runaway in the PCPS at room and cryogenic temperatures.

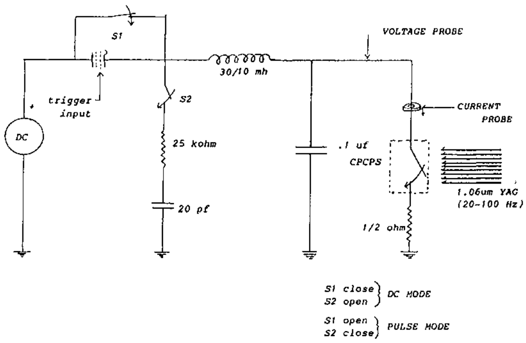

Fig. 1 Pulse and dc bias circuit.

Introduction

The photoconductive power switch has demonstrated capability of switching at very high power (~0.2GW) and high voltage a short (<5 ns) electrical pulse for systems where fast rise times and precise control are required.[1,2] However, to date this technology has been limited to short electrical pulse systems at low repetition rates. This paper addresses these two limiting factors by demonstrating the thermal runaway problem exhibited in silicon under long electrical pulses at high repetition rates. Thermal runaway is a description given to a device that experiences thermal instability due to Joules heating in the device. For this particular switch, we were able to show that this thermal instability onset occurred at a power dissipation density of 2.4 watts/gram/cm.[2]

The Experiment

We have conducted experiments at Los Alamos National Laboratory to study single and repetitive photoconductive power switching for some time.[1,2] The current emphasis is on repetitive switching at cryogenic temperature. The repetitive switching was demonstrated using the circuits shown schematically in Fig. 1. This circuit allows us to pulse charge or to place a constant voltage across the switch. By pulse charging the system we were able to obtain high voltage switching, which was not possible in the dc mode of operation. In the dc mode of operation the series switch was shunted to place a constant low voltage across the switch and load combination. These two modes of operation allowed us to set a base line comparison for thermal runaway at low and high electric field stress across the silicon switch.

Data were collected using a pair of 7912 Tektronix programmable transient waveform digitizers with a IEEE-488 interface connection to an HP-85 computer. This made it possible to collect and to store the voltage and current waveforms across the switch simultaneously. The voltage and current probes that were used in this experiment consisted of a 40-KV 1000X Tektronix passive voltage probe and a Pearson pulse current transformer.

The photoconductive power switch was made from one kohm-cm silicon crystal shaped into a cylindrical rod. Concave hollows were ground into the ends of the rod to allow brass electrodes to be attached. The electrical contact was made with Gallium:Indium (75.5:24.5). This gave good electrical contact between the brass and the silicon. For cryogenic operation, the switch and electrode assembly was immersed in a bath of liquid nitrogen.

A JK Hyper YAG laser system capable of repetitive pulsing up to 100 Hz was procured for this project. The laser was used to illuminate the switch with 10-ns FWHM laser pulses of 1064-nm radiation with energies of 120 mJ at 20 Hz, 100 mJ at 40 Hz, and 30 mJ at 100 Hz. Several methods, including fibers and lucite blocks, for delivering the light to the switch were investigated. However, most of the experiments, simple direct illumination through the liquid nitrogen bath was used.

Direct Current Operation

Operation at constant voltage was used to study thermal runaway and its effect on the switching characteristics. In this mode, the ohmic heating caused by the dark current in the switch changes the switch impedance in a complex way. Figure 2 shows the voltage versus current relationship as the power supply voltage is increased. Initially, there is approximately linear increase in current with voltage. However, at about 300 volts, there is an abrupt increase of the switch resistance. This is probably due to a change in the rate of heat transfer to the nitrogen bath. Observation of the switch at this point showed significant turbulence of the liquid nitrogen around the silicon rod.

Maximum heat transference between the silicon surface and the nitrogen bath seems to occur at the

*Funding through the Department of Energy

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **JUN 1987**	2. REPORT TYPE **N/A**	3. DATES COVERED **-**

4. TITLE AND SUBTITLE **Investigation Of Cryogenic Photoconductive Power Switches**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Los Alamos National Laboratory Los Alamos, NM 87545**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR’S ACRONYM(S)
	11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES

See also ADM002371. 2013 IEEE Pulsed Power Conference, Digest of Technical Papers 1976-2013, and Abstracts of the 2013 IEEE International Conference on Plasma Science. Held in San Francisco, CA on 16-21 June 2013. U.S. Government or Federal Purpose Rights License

14. ABSTRACT

Repetitive photoconductive power switching with a Nd:Yag laser at pulse rates up to 100 Hz was demonstrated at room and cryogenic temperatures. A silicon rod 3 em in length and 9 mm in diameter with a resistivity of 1 Kohm-cm was optically triggered in a circuit capable of allowing us to pulse charge the system or to bias the switch with constant voltage. In the pulse charge mode, an HY8 thyratron was used as a series switch to place a maximum of 1.25 J of stored energy in a 0.1 uf capacitor. This energy was t.hen delivered t.o a 0.5 ohm load by optically tr-igger-ing t.he photoconductive switch. In the direct current mode of operation, the triggering was perfor-med with a constant voltage across the switch and load combination. These two arrangements made it possible to study the effect of thermal runaway in the PCPS at room and cryogenic temperatures.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**SAR**	**4**	

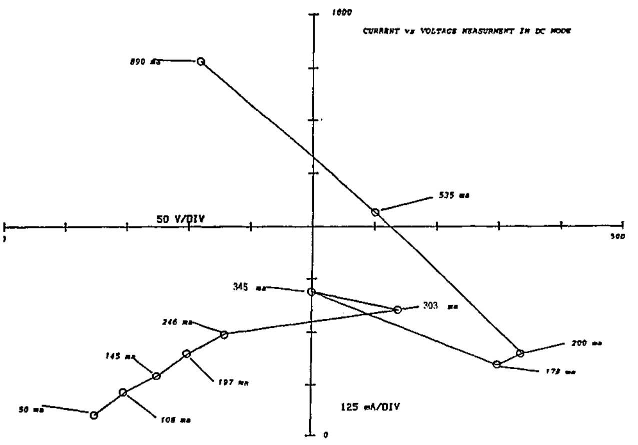

Fig. 2 Current-voltage characteristic plot during dc biasing at 77 K.

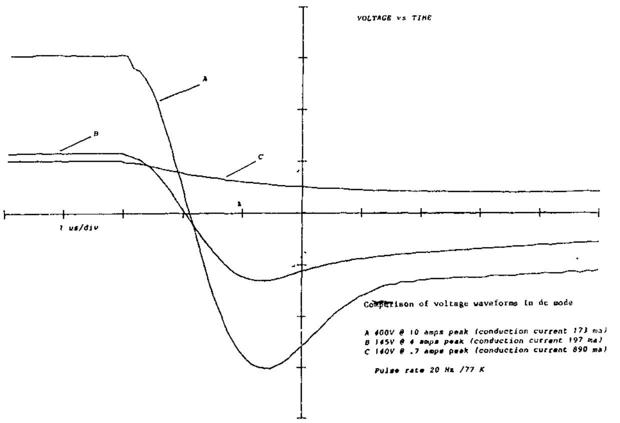

Fig. 3 Comparison of voltage waveforms during dc biasing at 77 K.

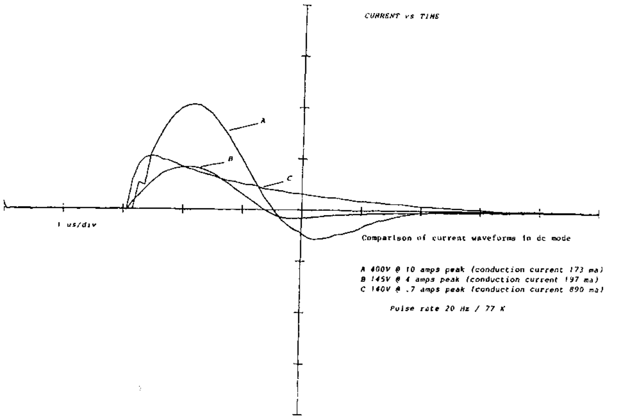

Fig. 4 Comparison of current waveforms during dc biasing at 77 K.

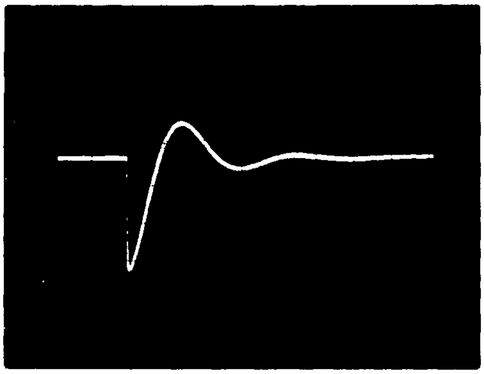

Fig. 5 Voltage switching transient with dc biasing at 77 K – 0.1 ms/div horizontal 20 v/div vertical.

liquid-vapor phase transition in liquid nitrogen. It is at this point of operation that the switch resides at a resistance value that is metastable.

As the voltage is further increased, to about 400 volts, an abrupt drop in the dark resistance occurs. We believe this is due to the onset of thermal runaway, which thermally generated carriers rapidly decrease the resistance, which, in turn, increases the IR^2 heating to produce a positive feedback mechanism. If the power supply were still, i.e., fixed voltage independent of current), the runaway might be catastrophic. However, as the voltage drops with increasing current, a stable position is reached.

The conduction currents of 50, 100, 150, 200, and 250 ma in Fig. 2 represent a power dissipation in the switch of 5, 10, 20, 30, and 45 watts. The switch has shown power dissipation of 70 watts for the metastable region and 90 watts at the onset of thermal runaway. This value can be used to determine the 2.4 watts/gram/cm^2 that represents the amount of power dissipated per unit mass per surface area of the silicon switch. The comparison of the voltage and current waveforms for the three regions, i.e., low-power dissipation (<45 W), metastable (60-75 W), and high-power dissipation (>80/ W), can be seen in Figs. 3 and 4.

In liquid nitrogen, approximately 125 watts must be dissipated in the switch to achieve runaway. This figure is about 18 times greater than the 7 watts observed to cause runaway at room temperature. Thus, the higher thermal conductivity of the silicon at liquid nitrogen temperature and the ability of the nitrogen bath to remove heat at a higher rate substantially improve the power handling characteristics of the cryogenic switch over room temperature operation in air.

When the switch is illuminated by a laser pulse in the dc mode, the photogenerated carriers decrease the switch impedance and transfer the voltage to the load. A characteristic voltage switching transient for relatively low dc bias is shown in Fig. 5. A train of such pulses at 20-Hz repetition rate is shown in Fig. 6. There is an overshoot of voltage when the switch opens as the photogenerated carriers recombine. We believe this is due to the inductance of the circuit. As the dark current in the switch increased, causing heating and a change in resistance, the degree of this overshoot first increases and then decreases. Near the thermal runaway condition, the overshoot disappears, thereby giving damped voltage and current waveforms. The shape of these waveforms proved to be a useful way of judging the temperature of the switch under different conditions and it was studied extensively.

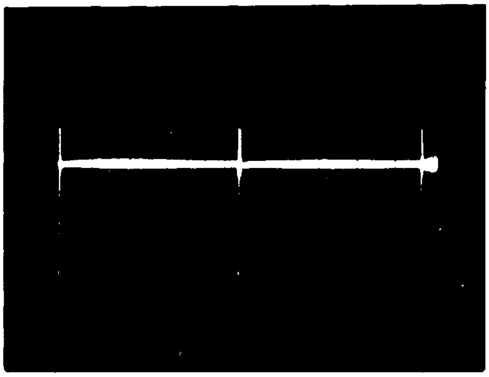

Fig. 6 Train of pulses at 20 Hz - 20 ms/div horizontal, 20 v/div vertical.

Pulse Charge Operation

Under pulse charging conditions, substantially higher voltages could be applied across the switch without causing thermal runaway. By pulse charging the system, a peak power of 0.29 MW was delivered to the 0.5 ohm load in 3 us. Figure 7 shows a pulse charge waveform switched by a laser pulse slightly after its peak voltage of 1000 V was reached. Figure 8 shows a train of such pulses at a 100-Hz repetition rate. Using pulse charging, the voltage could be increased to 4.1 kv at a 100-Hz rate before dissipation heated the switch near thermal runaway. Figures 9 and 10 show the voltage and current waveforms obtained from the two transient digitizers at the point of thermal runaway in the switch at room and cryogenic temperature. The RMS power dissipated in the circuit can be approximated as the peak power times the ratio of the pulse duration to that of the repetition rate. Using an on-time duration of 3 us and an off-time duration of 10 ms for the 100-Hz switching rate, the 4.1 KV pulse at 70 amps can be evaluated as an RMS power value of 86 watts. The power dissipation under these conditions corresponded closely to that observed for runaway under dc bias conditions at cryogenic temperature. Therefore, a simple trade off between voltage and pulse rate can be made to avoid thermal runaway.

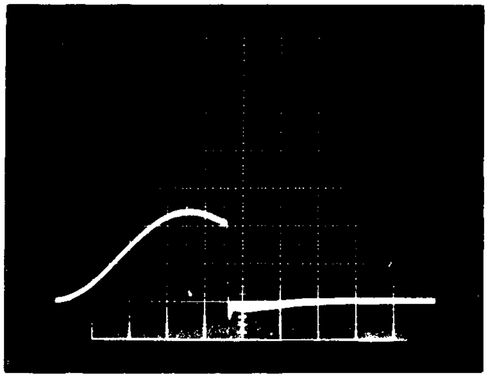

Fig. 7 Voltage switching transient with pulse charging - 20 us/div horizontal 500 v/div vertical.

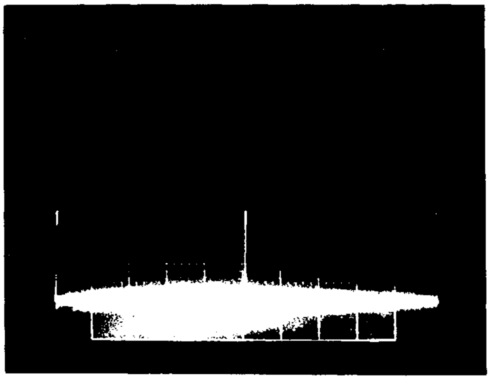

Fig. 8 Train of pulses at 100 Hz - 2 ms/div horizontal; 500 v/div vertical.

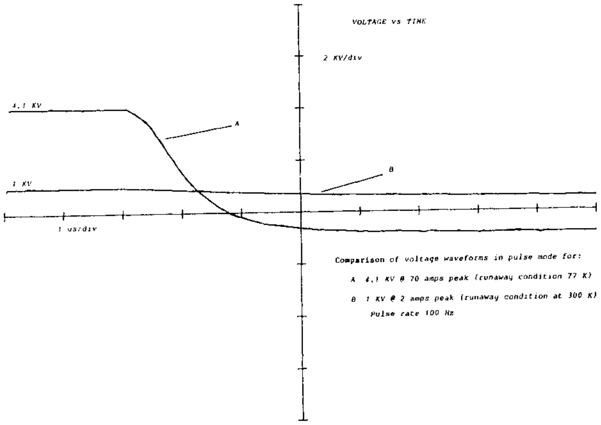

Fig. 9 Comparison of voltage waveforms during pulse charging at 77 and 300 K.

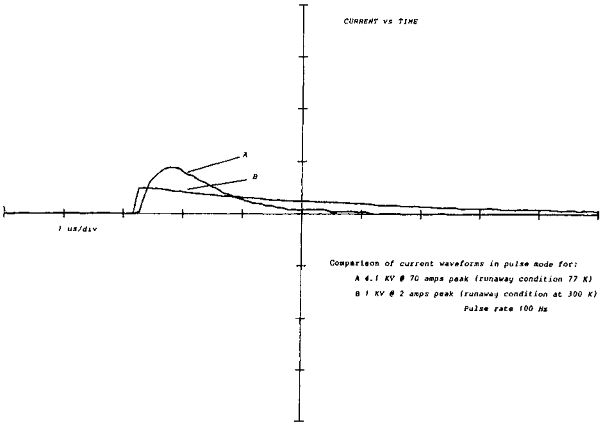

Fig. 10 Comparison of current waveforms during pulse charing at 77 and 300 K.

Conclusion

The photoconductive power switch is limited by the rate at which thermal energy can be removed from the silicon and by the average optical power available from the present 1.06-um laser system used to control the switch. These experiments have demonstrated that a photoconductive power switch can be repetitively switched with a Nd:YAG laser at pulse rates up to 100 Hz and that by cooling the 1 Kohm-cm silicon switch to liquid nitrogen temperature, the sample was capable of 2.4 watts/gram/cm^2 dissipation before the onset of thermal runaway. The cryogenic switch has shown itself capable of dissipating thermal heat generated in the switch 18 times better than room temperature operation.

Further improvements may be obtained by optimizing the switch geometry and illumination method for cryogenic operation and by using a silicon sample with a high resistivity.

References

[1] W. C. Nunnally, et. al., FY83, FY84 Progress Report, Electronic Division, Los Alamos National Laboratory report LA-9759-MS and LA-10360.

[2] W. C. Nunnally and R. B. Hammond, Appl. Phys. Lett. 44 (10) (May 15, 1984).