

PHOTOCONDUCTIVE SWITCHING OF A BLUMLEIN PULSER*

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Abstract

A four-stage parallel-plate gas insulated Blumlein pulser is under construction. This 90-ohm 16-ns (FWHM) pulser, targeted for operation at 400 kV, will be switched by an array of photoconductors triggered by a 15-J, Nd:glass laser for a 1-to-2-ns rise time. A smaller single-stage 100-kV 60-ohm 14-ns (FWHM) pulser, which has been used as a proof-of-principle testbed for the photoconductive switches, is the source of the data reported here. We report on the pulser designs, the diagnostics, and the details involved with the use of photoconductive switches.

Introduction

Optically controlled switches offer many advantages over the traditional arc switch. Arcs take a finite time to develop and involve statistical processes that complicate multi-channel switching. Synchronizing several arcs presents problems that are only partially solved by laser triggering.

These problems are theoretically solved with bulk photoconductive switches where a photoconductive material, such as Si or GaAs, bridges the electrode gap becoming conducting wherever it is illuminated. For each photon absorbed in the material, an electron/hole conduction pair is created in a time frame of 10^{-15} s. A simple argument would then suggest that the effective closure speed is determined by the rate with which sufficient photons can be applied to the material.

The conductivity of a photoconductor is given by the product of the elementary charge, the pair density and the effective drift mobility for the pairs. For densities below 10^{18} cm^{-3} , the mobility is constant and the conductivity is an exponentially decaying function of the depth into the illuminated surface. The e^{-1} distance or penetration depth in Si is about 0.5 mm for 1.06-micron photons, while it is only 4 microns for 694-nm (ruby) photons. The ultimate conductance of a switch of given length and width is simply related to the surface resistivity, which is determined by the density of conduction pairs produced in the material. The relation between the surface resistivity and the energy density of the incident illumination is illustrated in Figure 1 (in which we assume that the recombination time is much longer than the pulse width of the laser). Provid-

ing a larger volume for conduction (as is done by using 1060-nm photons on Si) helps to keep the pair density below the 10^{18} cm^{-3} level. Once the material becomes conducting, it remains so until the electrons and holes recombine.

Previously reported bench experiments¹⁻³ have made photoconductive switches an attractive alternative to arc switches. The main purpose of our work is to apply existing photoconductive technology to a moderately sized pulser and to bridge the gap between the bench work and the full-scale pulsers that would be of practical interest.

Si Versus GaAs

The characteristics of Si and GaAs differ substantially. While 1.06-micron photons carry sufficient energy to create a conduction pair in Si with a one-step process, in GaAs the photon energy is insufficient and the process proceeds via an intermediate level.

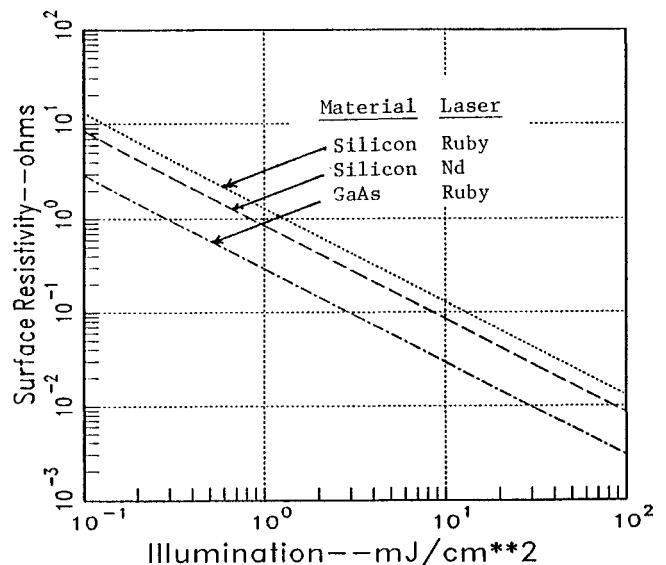


Fig. 1. Surface resistivity as a function of laser energy for a sampling of photoconductor/laser combinations when the illumination is applied over a short fraction of the recombination time.

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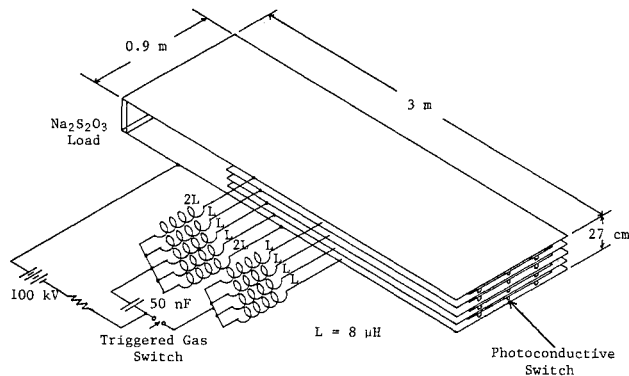


Fig. 2. Four-stage, parallel-plate Blumlein pulser.

The second difference is in the dark resistivity. Before illumination, Si has a resistivity of about 50 k-ohm-cm, while the GaAs resistivity is 10 M-ohm-cm. The ramification of this difference is that GaAs can be dc biased and the leakage current will be sufficiently small to avoid thermal runaway; Si must be pulse-charged within several microseconds.

The third difference is the recombination time. Intrinsic Si stays conducting for about 0.1 ms, while recombination in GaAs is about 10 ns. As a result of this difference a very short laser pulse is all that is required to switch Si for pulses as long as 0.01 ms. However, in GaAs to obtain pulses in excess of a few nanoseconds, the photoconductor must either be overdriven with a short burst of laser illumination, or it must be repeatedly (or continuously) illuminated to replenish the supply of charge carriers.

Pulser

In 1983 W. C. Nunnally⁴ proposed a stacked Blumlein pulser as a candidate for photoconductive switches. According to present plans, our version of this pulser (Figure 2) will be a stack of four 23-ohm Blumlein stages that discharge a 16-ns pulse into a 90-ohm $\text{Na}_2\text{S}_2\text{O}_3$ fluid resistor. The switches will be an array of Si cylinders, each 1 cm in diameter by 2.5 cm in length. The stages will be pulse-charged by a 100-kV, 50-nF capacitor bank through an array of 0.01-mH inductors.

In preparation for the four-stage pulser, we have conducted experiments with a smaller, single-stage, 30.5-cm-wide, 60-ohm, 14-ns Blumlein pulser (Figure 3). The resistors in this pulser have been adjusted during the course of the experiments to vary the pulse-charge rise time and the bank decay time. The switches on this pulser are similar in size to those that will be used on the larger pulser and are tested under similar voltage and current conditions.

Due to our 16-ns pulse length, we chose to work almost exclusively with Si switches. Two different types of intrinsic silicon

switches were used both having hemispherical indentations for contacts. For the first type gold was evaporated into the indentation at both ends of the switch. The second type employed 25-micron diffusion contacts with boron at one end of the switch and phosphorus at the other. The diffusion was accomplished by baking the switches at 1100°C for one hour. As a result of the baking process, the normal 0.1-ms recombination time was lowered to 0.001 ms.

Laser

The photoconductive switches are illuminated by an Apollo Model 35 laser system. This system, which has a Pockels-cell, Q-switched oscillator with a 0.5" by 8.5" Nd:glass rod and Brewster-angle polarizers, produces 2 J of 1060-nm photons in a 50-ns pulse. The pulse is narrowed to a width of 3 ns by a Pockels-cell shutter thrown by a light-activated spark gap. The narrow 200-mJ pulse is amplified by a pair of single-pass amplifiers (with rod sizes of 0.625" by 8.5" and 0.85" by 15.5") to a final energy of 15 J in a 2-cm-diameter beam.

Optics

The laser energy is incident on an acrylic homogenizer which provides a uniform distribution of light over the array of Fiberguide Industries Superguide 1000 fibers (1-mm-diameter nylon-clad silica) used to transmit the light to the various switches. One or more of these fibers is used to transmit a light sample to a Quantum Associates LPE-1 calorimeter. Another fiber transmits a light sample to a Hamamatsu R1328U-01 (60-ps) phototube for pulse-shape monitoring.

We also have acrylic homogenizers at the switch end of the fibers to provide a uniform illumination along the length of the photoconductors. At least three fibers run to each of these homogenizers, each of which is at least seven times the length of one fiber's share of the cross-sectional area of the homogenizer. The same scheme applies to the design of the homogenizer at the laser end of the fibers.

Electrical Diagnostics

The pulse charge of the Blumlein pulse-forming network is monitored with a CuSO_4 resistive voltage divider, while the current

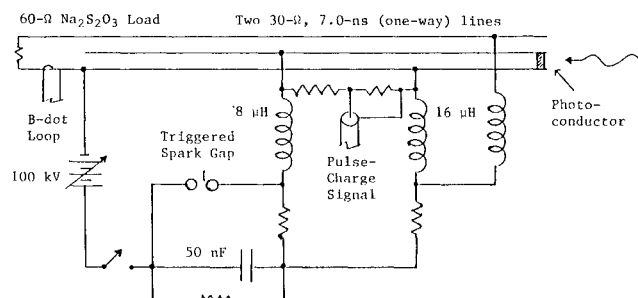


Fig. 3. Single-stage, parallel-plate, Blumlein pulser.

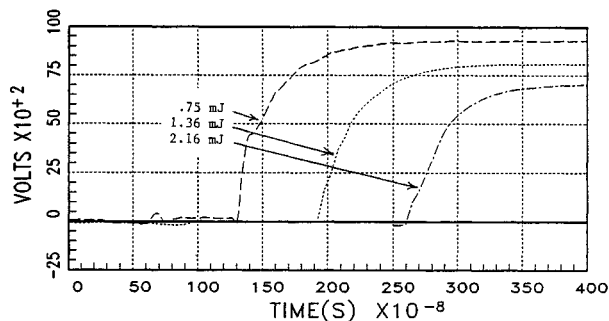


Fig. 4. Pulse-charge profiles for various illuminations on an unbaked Si switch.

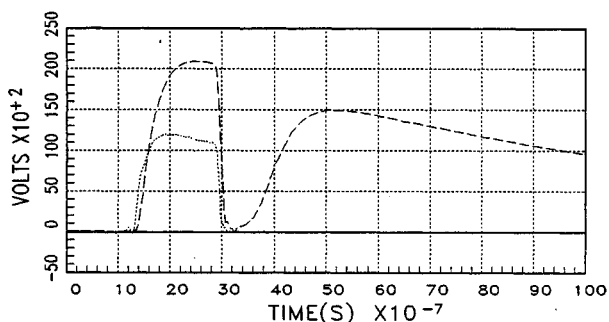


Fig. 5. Comparison of pulse-charge profiles with baked (dashed) and unbaked (dotted) Si switches.

into the dummy load is monitored with a B-dot loop with an L/R time of about 0.1 ns using about 40 ns of RG-214 cable. The optical pulse is recorded on the same trace as the output of the B-dot loop, which is delayed for pulse separation. The data are recorded with Tektronix 7104 oscilloscopes using 7A29 vertical amplifiers with 7B10 and 7B15 time bases. The B-dot signal is digitally integrated off line.

Data

Pulse Charge

Figure 4 shows a sequence of Blumlein pulse-charge profiles that correspond to a common voltage on the capacitor bank but different switch illuminations. (The switching occurs later in time than covered in the traces.) These profiles were made with the unbaked switches. The difference in amplitude can be attributed to the cumulative effect of the milli-watt-level illumination produced by the laser before Q-switching and shuttering, when integrated over the long recombination time of the switch.

A comparison of the pulse-charge profiles with baked and unbaked switches is shown in Figure 5 for a common level of illumination. The full (no illumination) amplitude of the pulse charge is obtained with the baked switch. However, following switching,

the recombination reopens the switch and the remainder of the decaying RC discharge of the capacitor bank appears on the Blumlein plates.

To avoid any cumulative effect of I^2R heating in the switch, the transition of the switch from its insulating to conducting states must be fast. Consequently, the amount of pre-illumination that can be tolerated with the baked switches is significantly greater than with the unbaked switches. However, a similar problem occurs as the carriers recombine. Since there is still bank voltage available as the baked switch opens, the relatively slow opening of the switch could be disastrous at higher levels of operation. To ameliorate this problem, future work will involve a faster bank. With an unbaked switch that has possibly suffered some pre-illumination, the voltage will then be applied to the switch for as short a time as is reasonable. With a baked switch the benefit will be during recombination with a negligible residual voltage on the bank.

One might attempt to lessen the pre-illumination with either a saturable dye or an additional Pockels-cell shutter at the laser output. Since a suitable Pockels cell is not available to us at this time, we are presently experimenting only with a dye cell. The results will be forthcoming.

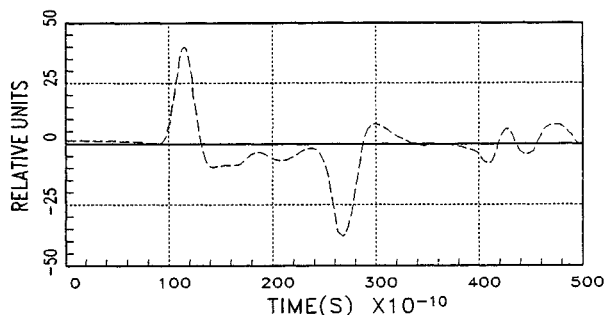


Fig. 6. Unprocessed B-dot trace at the load.

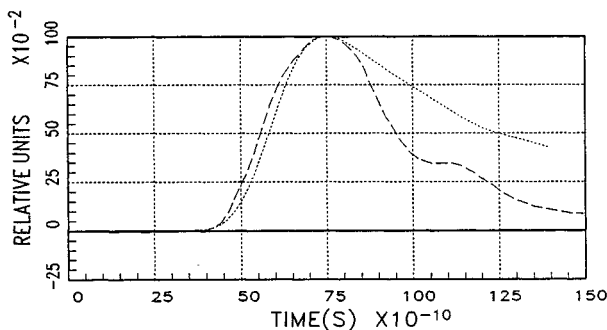


Fig. 7. Overlay of the load current from an integrated B-dot signal on the profile of the laser burst.

Output Pulse

A B-dot trace representative of the pulser output is shown in Figure 6. Figure 7 shows an overlay of corresponding traces for laser power and load current. The 2-ns width of the B-dot pulses represents the best rise time we have attained so far. Although one might believe that one need only increase the laser energy to supply more photons to the switch in a shorter time to obtain a faster rise time, we have not found this to be the case. With either type of switch we have found that, although increasing the laser power does improve the rise time down to the apparent 2-ns limit, increasing the laser power surprisingly results in a decrease in the output current even under conditions of an apparently consistent pulse-charge voltage. The optimal performance of our switch has been realized at an illumination level of 2 mJ.

A minimal amount of data were taken with a resistive divider across the load. These data show that there is a significant pre-pulse on the load draining energy that would otherwise be available to the main pulse, even when the baked switch is used.

Conclusions

We have demonstrated the usage of Si photoconductive switches up to 40 kV with fields of 16 kV/cm and with output-pulse rise times near 2 ns. This operation utilized 2 mJ of energy on each of three 2.5-cm-long switches although the benefit of 2 additional switches was marginal. Baked silicon switches offer much that we have yet to take

advantage of. Pending the resolution of the pre-illumination as seen with the smaller pulser, we plan to finish the construction and testing of the larger pulser during August 1987.

References

- [1] W. C. Nunnally, "Photoconductive Pulse Power Switches: a Review," in Proceedings of the 5th IEEE Pulsed Power Conference, 1985, pp. 235-241.
- [2] L. Bovino, T. Burke, R. Youmans, M. Weiner and J. Carter, "Recent Advances in Optically Controlled Bulk Semiconductor Switches," in Proceedings of the 5th IEEE Pulsed Power Conference, 1985, pp. 242-245.
- [3] F. Zutavern, M. O'Malley, M. Buttram, and W. Stygar, "Photoconductive Semiconductor Switching for Pulsed Power Applications," in Proceedings of the 5th IEEE Pulsed Power Conference, 1985, pp. 246-249.
- [4] W. C. Nunnally, "Photoconductive Pulse Power Switches," in Proceedings of the 4th IEEE Pulsed Power Conference, 1983, pp. 620-623.

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