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Abstract

This paper outlines the advantages and the potential of photoconductive switches applied to pulse power systems. The photoconductive effect can be used to switch large amounts of energy by changing the conductivity of a solid-state circuit element many orders of magnitude with a high-power laser. The simplicity of these devices offers many advantages in pulse power applications when combined with high-power pulsed lasers. The surge capability, the switched energy gain, and the maximum average power for photoconductive power switches are discussed. In addition, the results of a 100-kV, 100-MW photoconductive switch experiment transferring 20 J in 200 ns are presented.

Introduction

The preliminary development and demonstration of scalable, photoconductive power switches (PCPSs) at Los Alamos¹⁻³ indicate that it is theoretically possible, in a single solid-state device, to switch high voltages (megavolts at 100 kV per cm length) and high currents (megamps at 10 kA per cm width) with more precision and higher efficiency than with any other technology. PCPSs operating at 135 kV (65 kV/cm) and 2 kA (4 kA/cm) have been experimentally demonstrated.¹ Because PCPSs can be designed to close faster with less inductance and less relative jitter than any other technology, power conditioning systems can be simpler, more efficient, and more compact. The large specific heat and the excellent thermal conductivity of photoconductive materials make the technology applicable to a large number of high-energy, high-average-power pulse applications.

Photoconductive Power Switch

Physical Description

The basic PCPS geometry is illustrated in Fig. 1. Electrodes make contact at the ends of a photoconductive material such as silicon, GaAs, or InP. Because photoconductivity is a bulk phenomena, a single

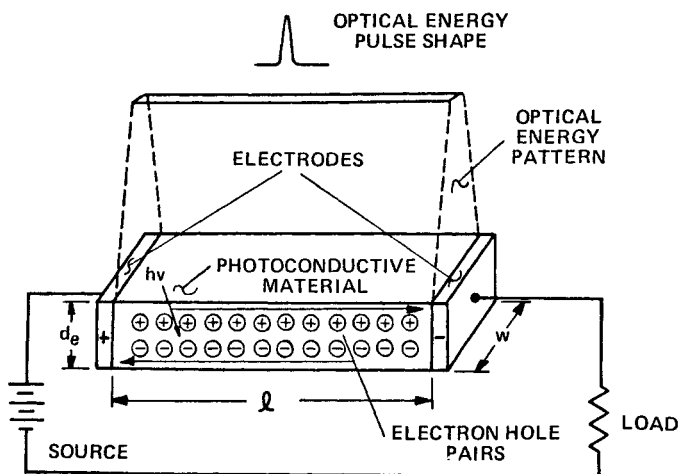


Fig. 1. Photoconductive power switch geometry.

device can be scaled to any voltage or current requirement. The length l of the photoconductive material block is determined by the desired operating voltage; the width w is determined by the desired operating current or desired inductance; and the effective optical absorption depth d_e is determined by the type of photoconductive material and by the optical control wavelength.

This arrangement differs from the light-activated silicon switch (LASS)⁴ in two aspects. First, the LASS device uses the four-layer, silicon-controlled rectifier (SCR) structure with three series PN junctions, one of which must hold off the applied voltage before switching, while the photoconductive power switch distributes the applied voltage across the entire length of the photoconductive material between the electrodes. Second, the region between the electrodes is uniformly illuminated in the PCPS to change the conductivity of the entire device simultaneously, while the LASS device uses the photoconductive effect to change only the conductivity of the gate region of the SCR structure.

Operation

1. Optical control. The conductivity of a PCPS can be controlled with electrons, ions, or photons. For the purpose of this discussion, only photon sources will be considered. Optical control has the inherent advantage of isolation for any high-voltage switch. For a PCPS, optical control has the further advantage of very fast closure of the switch due to the large amount of optical energy that can be delivered in a very small period of time in a high-power laser pulse. In addition, the optical energy can be distributed in space with very precise time resolution to control one large switch or many separate switches either simultaneously or in a precise sequence determined by the transit-time differences of the controlling optical path lengths.

2. Bulk Carrier Generation. A photon with an energy greater than the photoconductor band gap produces an electron-hole pair in the photoconductive volume. When uniformly illuminated, the conductivity of the entire switch can be changed in the time in which the optical energy is delivered. The bulk generation of electron-hole pairs in the conduction volume removes the transit-time limitation of device speed that is present in other switching technologies. Thus, device speed is decoupled from device size or power. As illustrated in Fig. 2, a PCPS can be closed in a time scale not possible with other technologies. The change in resistance or closure of a conventional switch is initiated at a single point between the electrodes. Avalanche processes must then generate additional carriers. However, as the carrier density increases, the electric field in the switch decreases, reducing the carrier generation rate. Thus, conventional high-power switches have a decaying exponential resistance during turn-on. In contrast, the resistance of the PCPS is determined by an external optical source with closure time determined by the optical power.

3. Carrier Removal. The carriers generated with the input optical energy are removed from the conduction process in two ways. First, the carriers

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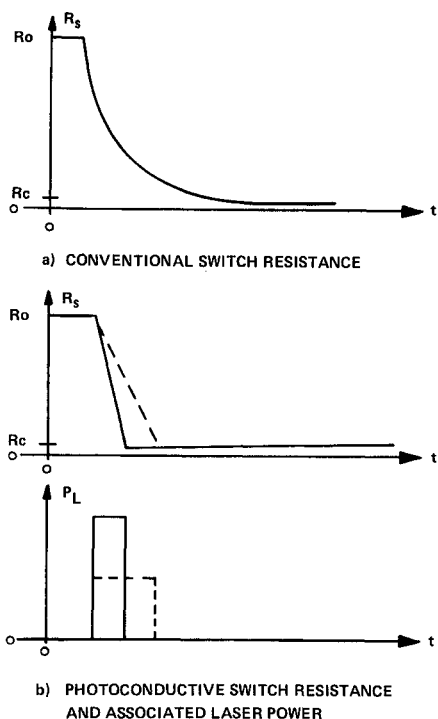


Fig. 2. Comparison of conventional and photoconductive switch closures.

recombine within the photoconductive material in a time determined by the trap doping level. For very highspeed photoconductive detectors, the recombination time is chosen to give the fastest possible falloff. As shown in Fig. 3, heavy doping produces recombination times less than 100 ps. For a closing switch, long recombination times are desired so that conduction will persist after the end of the optical pulse. Recombination times of 20 μ s have been measured at Los Alamos in intrinsic (pure) single-crystal silicon so that electrical pulses with durations less than 1 μ s can be switched with a much shorter optical pulse. The conductivity in the switch can be maintained by supplying additional optical energy during conduction.

Carriers are also removed from the conducting volume at the contacts. If the junction between the metal and the conductor forms a Schottky barrier, only a fraction of the carriers will be reinjected. To maintain high conductivity, the contacts must be ohmic in nature without a Schottky barrier.

Limitations

The operating voltage of a PCPS is limited by the electric breakdown of the photoconductor or its surface. The bulk electric field strength of most semiconductors is about 100 kV/cm, and initial experiments at Los Alamos have operated at up to 65 kV/cm, and improvements are being developed.

To avoid thermal runaway in a silicon PCPS, the carrier density must remain below 10^{18} cm^{-3} . This translates into a current density of less than 100 kA/cm² or a line current density of 10 kA/cm with an optical absorption depth of 1 mm. Experiments at Los Alamos have demonstrated a line current density of 4 kA/cm.

The electrical pulse length and the pulse repetition rate are limited by the average power obtainable with present laser systems. However, many low-pulse rate applications with electrical pulses less than 1 μ s are possible with present-day lasers.

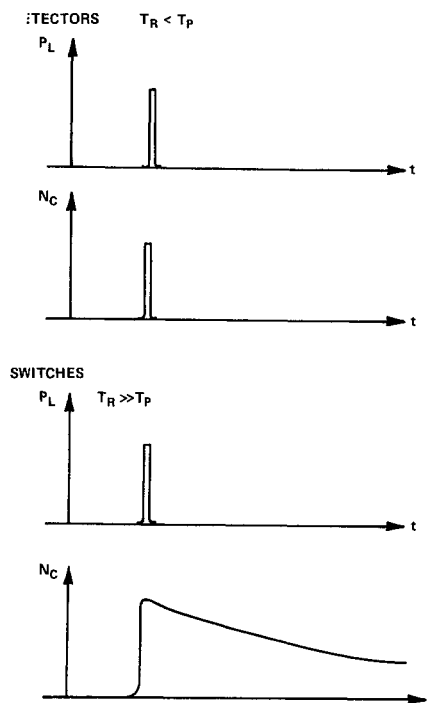


Fig. 3. Photoconductor recombination times for detectors and switches.

Additional Advantages

1. Circuit-Independent Control. The conductivity of a PCPS is controlled by the external optical source and not by the circuit to which it is connected. Thus, a PCPS designed to operate at 10 kV should close in a similar manner at 10 V.

2. Inductance-Resistance Ratio. Because the inductance of a PCPS is proportional to its width and the resistance is independent of width, the ratio of the switch inductance to resistance can be designed for a specific application by varying the switch width.

3. Thermal Management. For fixed total optical input, the total resistance is independent of width. Electrical energy dissipated per unit volume in the switch is reduced by increasing the width of the switch. The area available for heat removal also scales as the width of the device so that the maximum average power of operation scales as the width of the switch. The thermal energy deposited in the switch must be transported only the effective optical absorption length to the large surface area and must be removed from the conducting medium.

4. Implementation of Alternate Circuit Concepts. The fast closure, precise control, optical isolation, and low inductance possible with PCPSs make the implementation of standard circuits more efficient and the application of alternate concepts feasible. For example, the switching of a Blumlein line⁵ pulse generator with a high-efficiency, very low-inductance PCPS is illustrated in Fig. 4. The use of the PCPS with the Blumlein line will provide a faster output pulse risetime and reduce the percentage of stored energy deposited in the switch compared with that of conventional technology, especially in very low-impedance systems. The control of a single Blumlein line can be extended to the stacked line⁶ concepts illustrated in Fig. 5.

BLUMLEIN LINE MODULE

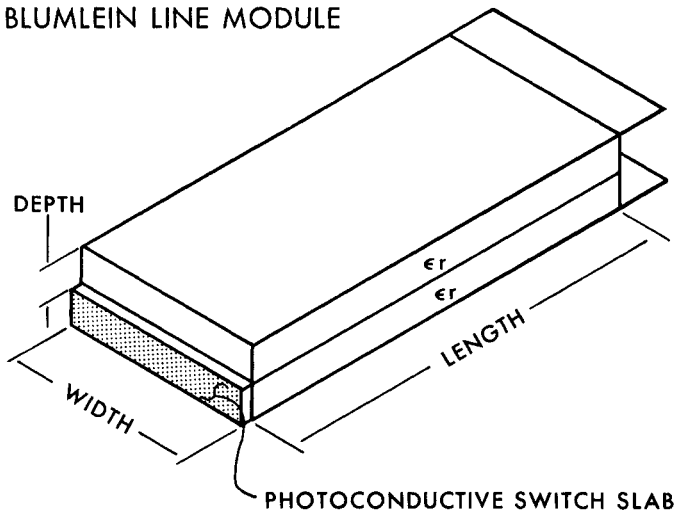


Fig. 4. Photoconductively switched Blumlein line pulse generator.

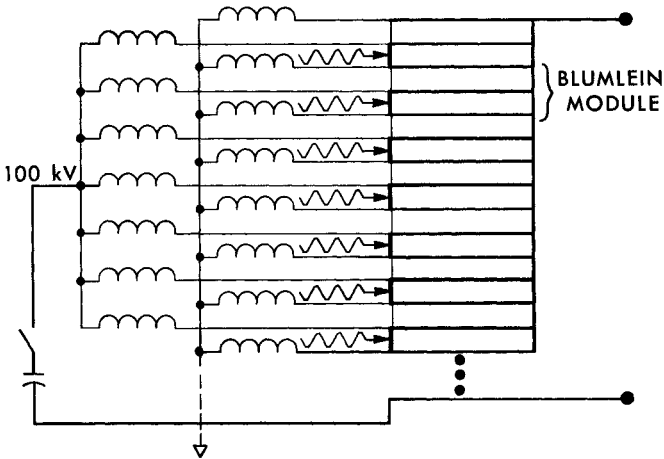


Fig. 5. Photoconductively switched stacked line module.

Analysis

Photoconductive Switch Resistance

The resistance R_s of the photoconductive volume of Fig. 1 is given by¹

$$R_s = \frac{2\ell E_\lambda}{[e \mu E_L (1-r)]} \quad (1)$$

where e is the electron charge, μ is the sum of the carrier mobilities, E_L is the optical energy, r is the material reflectivity, and E_λ is the photon energy. Note that the photoconductive resistance is independent of width for constant optical energy deposited in the photoconductive volume.

Adiabatic Characteristics (I^2t)

The amount of energy that can be absorbed by a switch is determined by the I^2t product. The value of the I^2t product for a photoconductive power switch when an infinite recombination time is assumed is given by¹

$$(I^2t)_c = \rho w d_e c_p \Delta T e \mu (1-r) E_L / (E_\lambda \ell) \quad (2)$$

where c_p is the material specific heat, ρ is the material density, and ΔT is the change in device temperature during conduction. Note that junction devices are limited to a maximum temperature of 180°C but PCPSs can operate with much higher values of ΔT . As an example, for $E_L = 10$ J, $w = 1$ m, $\ell = 0.1$ m, $\Delta T = 1000^\circ\text{C}$, $r = 0.3$, $c_p = 0.7 \times 10^3$ J/kg-°C, $\rho = 2.33 \times 10^3$ kg/m³, $\mu = 0.13$ m²/s, and $E_\lambda = 1.2 \times 10^{-19}$ J for 1.06- μm wavelength illumination, $I^2t = 1.5 \times 10^7$ A²s. Thus, this switch will conduct a current of 10 MA for time $t_{ep} = 150$ ns with an optical trigger energy of 10 J.

Switched Energy Gain

The switched energy gain of a photoconductive switch is best described as the ratio of the energy transferred to the load to the laser energy incident on the surface. If a matched system is considered where the source impedance is equal to the load impedance and the switch resistance is much lower than the load impedance, then energy delivered to the load (assuming that the electrical pulse risetime is much less than the pulse length) is¹

$$E_{load}/E_L = \rho w d_e Z_L E_{max} C_p \Delta T e \mu (1-r) / (V_s E_\lambda) \quad (3)$$

where the switch length is the ratio of the source voltage V_s to the maximum electric field E_{max} and Z_L is the load impedance. The switched energy gain is limited by the amount of heat that the switch can absorb before damage occurs.

Maximum Average Power

The maximum average power delivered to a load through the switch is related to the maximum average power that can be removed from the switch volume at a temperature consistent with switch operation. The average power delivered to the load in a repetitively pulsed system is

$$P_{avg} = I^2 R_L t_{ep} PRR = h(T_{edge} - T_{fluid}) \gamma w \ell / \delta \quad (4)$$

where I is the current through the switch, R_L is the load resistance, t_{ep} is the electrical pulse length, PRR is the pulse repetition rate, h is the heat transfer coefficient between the switch and the cooling fluid, γ is some multiple of the switch frontal area available for cooling, w is the switch width, ℓ is the switch length, δ is the ratio of the switch resistance to the load resistance, and T_{edge} and T_{fluid} are the temperatures of the switch body and the cooling fluid, respectively. If $h = 1000$ J/s $R_L = 0.01 R_L$, $\delta = 0.01$, $(T_{edge} - T_{fluid}) = 100^\circ\text{C}$, $\ell = 0.1$ m, $w = 1$ m, $\gamma = 10$, $t_{ep} = 100$ ns, $I = 50$ kA, 100 ns, and $PRR = 10$ kHz, then the peak power delivered to the load is 10 GW, and the average power delivered to the load is 10 MW. The average power that must be removed from the switch in this example is equal to γP_{avg} or 100 kW.

Experimental Results

Initial high-power evaluations of the PCPS were conducted at Los Alamos using the experimental arrangement shown in Fig. 6. Two 60-ft coaxial cables were pulse charged to voltages between 50 and 225 kV with a Marx bank and switched into a matched resistive load with a PCPS. The PCPS was a 2.2-cm-long by 0.5-cm-square single-crystal, intrinsic silicon bar with aluminum deposited on the ends for electrodes. The PCPS was switched with a Q-switched Nd:glass laser with a 20-ns FWHM pulse, a risetime of approximately 5 ns, and optical energies between 0.03 and 3 J.

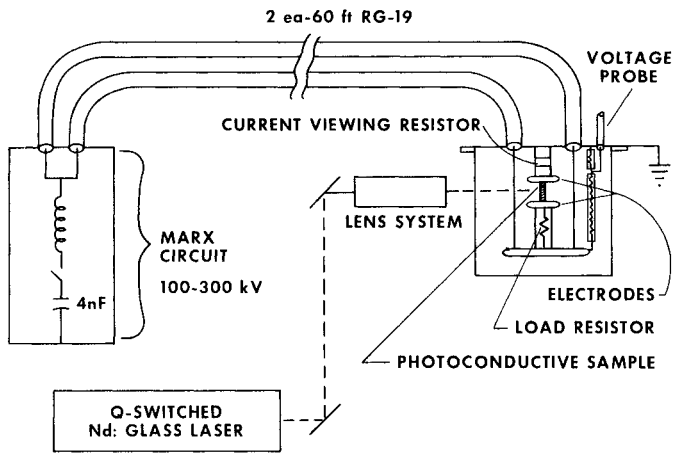


Fig. 6. Experimental arrangement for photoconductive pulse power switch.

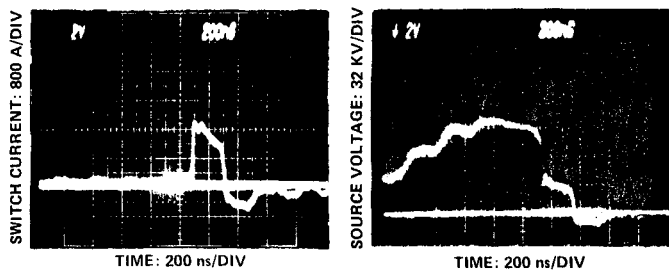


Fig. 7. Photoconductive pulse power switch experimental results.

The coaxial cable or source voltage and the switch current shown in Fig. 7 indicate that the switch, in this instance, held off about 100 kV or an electric field of 45 kV/cm and conducted a peak current of about 1.7 kA for 200 ns. Note that the optical control pulse terminated after 20 ns and the current continued to flow through the switch. The decay in the switch current observed in Fig. 7 with a characteristic decay time of about 200 ns is a result of contacts that did not reinject the carriers swept from the conducting region during the calculated 250-ns transit time.

Conclusions

Photoconductive pulse power switches have the potential to close faster (and thus more efficiently) with more precision, less relative jitter, and with less inductance than any other technology. They also offer the standard advantages of optical control isolation. The bulk nature of the photoconductive phenomena will permit the design of a single, solid-state switch for any voltage or current or of multiple photoconductive switches to be closed in a precise sequence. The thermal characteristics of photoconductive materials and a geometry that promotes heat removal permit very large surge capabilities and large average power operation.

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