RECENT ADVANCES IN OPTICALLY CONTROLLED BULK SEMICONDUCTOR SWITCHES

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Summary

The ERADCOM Optically Activated Switch (OAS) Program has as its goal the development of a family of optically controlled bulk semiconductor power switches capable of operating over a wide range of specifications. Various combinations of switch material and optical emitter have been tested. The best overall success has been achieved by coupling GaAs or Cr:GaAs switches to a Q-switched Nd:YAG laser or to high power laser diode arrays. The laser diodes provide for high repetition rates while the Nd:YAG laser provides sufficient optical energy to switch megawatt pulses. Results obtained with both configurations, as well as OAS design considerations, are discussed.

Introduction

Optically controlled switches offer many advantages over high voltage switches traditionally used for pulsed power applications. The Optically Activated Switch is simply a bulk, three terminal device (the third terminal being the optical input), fabricated from high resistivity semiconductor such that, as a switch, it is normally open and conducts negligible leakage current when DC biased at a substantial fraction (> 10%) of its theoretical breakdown voltage. The conductivity of the device is modulated by illumination with light of a wavelength suitable for carrier generation in the specific material. For semiconductors with sufficiently short carrier lifetimes, the current pulse closely resembles the optical pulse. Carrier lifetime can be as short as 1 ns for some switch materials. The relative advantages of the OAS, as well as some of its drawbacks, have been previously described.[1,2]

The optical source is a major consideration in the design of OAS devices. In most configurations, the optical source, not the switch itself, sets the limitations with regard to performance. For example, a Q-switched Nd:YAG laser has a fast risetime and sufficient energy per pulse to close even a very large switch, but its repetition rate is limited to about 1 kHz, or at best, millisecond bursts of up to 100 kHz. Individual laser diodes, on the other hand, can be modulated at PRF's up to 100 MHz, but do not emit sufficient optical energy per pulse to close even a relatively small high voltage optical switch. Recent advances in arraying laser diodes and in fiber optic technology have made available diode laser arrays capable of delivering optical pulses of sufficient energy to efficiently close moderate sized switches. However, due to the inductance of these arrays and the high current requirement of the diodes, risetimes are limited to the 5-10 ns range. Thermal problems limit the duty cycle of these devices to 0.1%, thus limiting the PRF to tens of kilohertz.

Two design approaches for the optically activated switch are discussed here. The first unites a high power, fiber coupled, laser diode array with a Cr:GaAs switch. The second couples a Q-switched Nd:YAG laser to a somewhat larger GaAs switch. Experimental data for both configurations is presented and design considerations with anticipated operating ranges are discussed. A computer model which describes the transient conductivity and electric field profiles in the semiconductor is described.

Discussion

Laser Diode Activation

The laser diode controlled switch couples a Laser Diode Laboratories model LDT-391 diode laser (Figure 1) to a Cr:GaAs switch of the design shown in Figure 2. The LDT-391 consists of four separate LDT-350's. Each LDT-350 consists of an array of 12 single heterojunction GaAs laser diodes, emitting at a wavelength of 0.904 microns. Each diode is individually fiber coupled to the output of its LDT-350 and the light from the four LDT-350's is combined in a solid glass integrator with an output aperture of approximately 0.5 mm by 0.5 mm. The specially designed "nosepiece", which houses the last inch or so of the integrator, extends the output aperture beyond the main frame of the laser, which is metallic. This extension provides the necessary high voltage isolation between the laser and the switch. The overall array is rated at 430 watts of optical power for a 200 ns pulse when driven with 40 amperes. At a 50 ns pulsewidth, the device can be driven with 60 amp peak currents and will provide a peak power of approximately 700 watts.

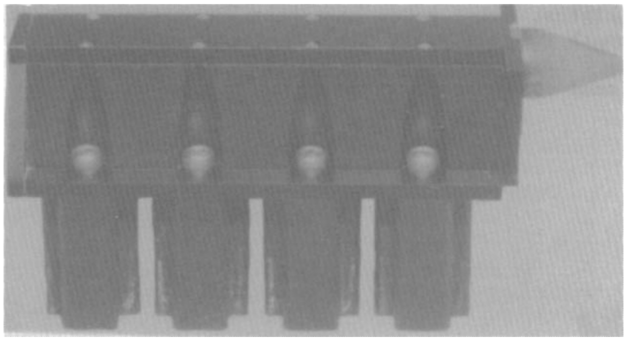

Figure 1. LDT-391 Laser Diode Array w/"nosepiece"

The switch (Fig. 2) is fabricated on a piece of wafer approximately 5 mm wide by 10 mm long by 0.4 mm thick. The electrodes, 50 angstroms Ni, 450 A Au, 200 A Ge, 1000 A Ag, capped with 4000 A Au, are 2 mm wide and deposited on opposite sides of the chip as shown. The electrode separation ranges from 0.5 mm - 3.0 mm. Switches having this geometry provide DC voltage hold-off of up to 3 kV per millimeter of separation or "gap length" and have been observed to routinely and repetitively carry current pulses of up to 30 amperes. The carrier lifetime in Cr:GaAs or GaAs ranges from 1 - 30 ns and PRF capability in this type of switch has been demonstrated to 100kHz[1].

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In this configuration, on-state resistances as low as 25 ohms have been achieved in a 1 mm gap length GaAs switch with approximately 30 microjoules of incident optical energy. It should be mentioned that, of the incident energy, about 25% is transmitted through the switch because of the relatively long absorption length and approximately 30% is reflected from the surface due to the mismatches of the indices of refraction of air and GaAs. The results show that, with careful switch design and improved optical coupling, laser diode arrays may provide sufficient optical energy to lower the switch resistance to 1 ohm or less.

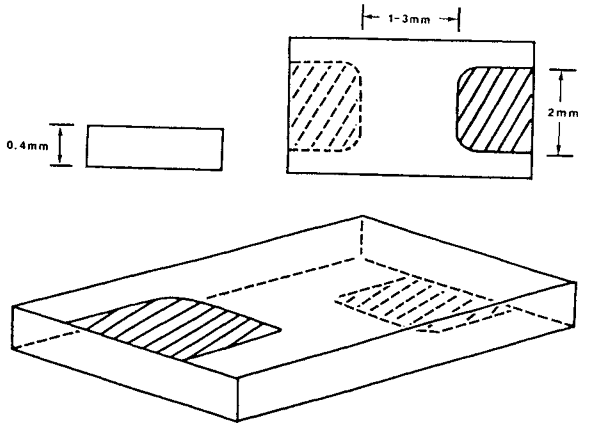


Figure 2. Laser Diode Controlled Switch

The laser diode controlled switch will operate in the range of 1 - 10 kV and carry pulsed currents, conservatively estimated, of up to 100 amperes. The pulse width, risetime, and PRF of the switch are determined by the laser. Current state-of-the-art provides the capability to drive the LDT-391 or a similar array at pulse widths of 20 - 200 ns, with risetimes of 5 - 10 ns, at PRF's up to 100 kHz. Duty cycle is limited by the laser itself. Improvements in the design of drivers for laser diode arrays could lead to subnanosecond risetimes and PRF's of several hundred kHz.

Nd:YAG Laser Activation

The Nd:YAG activated bulk semiconductor switch couples a Q-switched Nd:YAG laser (1.06 microns) to a GaAs switch of the design shown in Figure 3. The laser has a 50% pulse width of 25 ns and a full power pulse energy of 150 millijoules. Usually, pulse energy is reduced to 20 millijoules using neutral density filters. The beam diameter is approximately 7 mm.

The switch (Fig. 3) is a rectangular bar of semiconductor with a square cross section of 5 mm by 5 mm. The contacts are of the same composition as those on the laser diode activated switch and are indented 2 mm into the square faces to help prevent surface breakdown. Switches with gaps of 5 mm and 10 mm have been tested. These switches provide DC voltage hold-off of up to 4 kV per millimeter of gap length. Because of their greater cross sectional area these targets have demonstrated a current carrying capability of up to 1000 amperes pulsed. Recovery time and therefore PRF capability are similar to the smaller device. At 20 millijoules per pulse, the Nd:YAG laser reduces the switch resistance to less than 1 ohm in both the 5 mm and 10 mm switches. The low resistance is obtained in spite of the fact that the laser does not fully illuminate the gap of the 10 mm device. The risetime and width of the switched current pulse are dependent on the laser pulse shape and the pulse forming network (PFN) in the switch circuit.

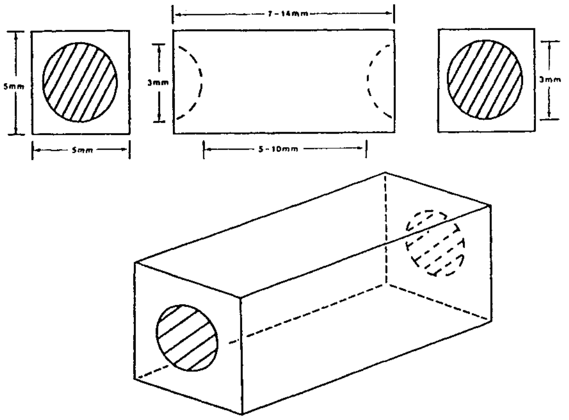


Figure 3. Nd:YAG Laser Controlled Switch

Since a Nd:YAG laser can provide a great deal of energy per pulse, the switch element in this configuration can be almost indefinitely scaled in size to increase power handling capability. Previous experiments[8] have demonstrated that Nd:YAG activated silicon switches of similar design (with length >2 cm) can be pulse biased to 160 kV while carrying pulsed currents of up to 2 kA. The main advantage of GaAs over Si switches is that they can be DC biased without the risk of thermal runaway and still draw less leakage current than a pulse biased Si switch. This greatly reduces the size and complexity of the charging circuit.

Computer Model

The conductivity and electric field profile in an optically controlled semiconductor is dependent on numerous factors. Several of the more important factors are listed:

1. Spatial/temporal variation of the light signal.
2. Contributions from hole as well as electron carriers (with different velocities for each type of carrier).
3. Carrier injection efficiency at the electrodes.
4. Space charge effects.
5. Transit time effects.
6. Displacement current (i.e., consideration of the semiconductor capacitance.)
7. Carrier traps (including the effect of the immobile charge on the field).
8. Recombination of carriers.
9. Dependence of carrier velocity on field.
10. Geometry.
11. Effective carrier generation rate.

The complexities are such that the operation of the optical switch usually depends on several of these factors simultaneously. In addition to design considerations, there is also the more general problem in which carrying out an accurate comparison between theory and experiment is often impossible because various factors are neglected. Unfortunately no computer code exists which takes into account all factors. In order to address this situation, a calculational technique is being developed which deals with the majority of the issues. Following is a discussion of those items which are simplified or neglected in this technique:

In the case of geometry (factor 10) the problem is assumed to be one dimensional, i.e., there is no variation in the plane perpendicular to the carrier motion (variations in the direction of the carrier motion are, of course, allowed). Changes in the perpendicular plane may be caused, for example, by the exponential absorption of the light signal. In most cases, however, a simple modification of the one dimensional result is satisfactory to account for light penetration. In a related issue, the probability of generating a carrier pair with a given photon energy is assumed known. Direct recombinaton, for the present, is neglected. In silicon this assumption is fairly good. For the III-V compounds, the assumption is reasonably good provided the carrier densities are not too large (carrier density < $5*10^{17}/cm^3$). If we neglect recombination, the dominant loss is trapping. To further simplify matters, the hole and electron transition frequencies for trapping are assumed constant. Trap filling effects are neglected. Finally, the most serious omission is considered, namely, the neglect of the carrier velocity dependence with field. Both hole and electron velocities are assumed constant. This assumption, together with the previous constraints, results in a complete linearization of the problem, allowing for simple closed form solutions. It should be mentioned, however, that these solutions provide a starting point from which the higher order nonlinear problem may be treated, including the velocity dependence on field. The major elements of the calculation are shown in the block diagram, Figure 4.

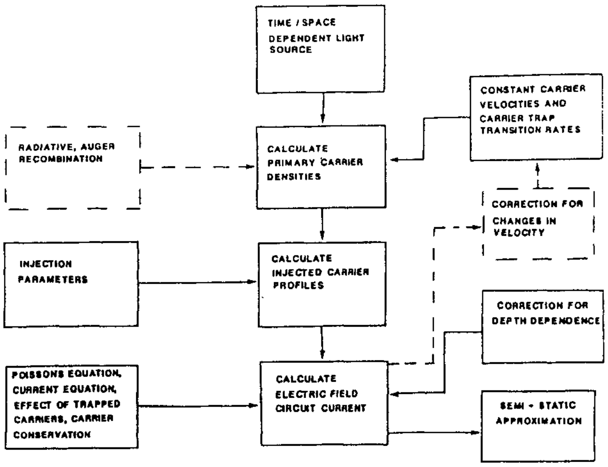


Figure 4. Computer Technique for Photoconductive Switch Model.

The equations which must be solved are the particle conservation equation, the current continuity equation, and Poisson's equation. The light signal determines the particle densities, which in turn determines the current and field profiles. For simplicity it is assumed that the external circuit is purely resistive. Carrier current injection at each electrode is assumed to be determined by a constant factor which relates the injected carrier current at one terminal to the carrier current leaving the semiconductor at the other terminal.

The calculational technique is, to some degree, a matter of choice. The approach chosen was to solve the equations by a bootstrap technique, whereby various time domains are first specified. These domains are determined by the relative locations of the carrier fronts. Continuity of the current (in time) and of the electric field (both time and position) is required during the successive stages in each domain.

As an example of the results of the analysis, the consequences of non-ohmic contacts is discussed. The results point out the importance of high injection efficiencies in order to prevent the build-up of large space charge fields in the semiconductor. As is well known, when the injection efficiency is perfect, the hole density exactly balances the electron density, and the space charge field is zero. However, if the injection efficiencies depart from unity by even a very small amount, large space charge fields may develop, particularly near the electrodes. Figure 5 shows the field profiles for various hole and electron injection efficiencies. Note the increased non-uniformity in the field as the injection efficiency is lowered. The profiles shown are for the case of negligible trapping and for a uniform carrier pair generation rate of 1.25 * $10^{18}/cm^3$-sec. It should be pointed out that these large fields, particularly when they develop near the electrodes, probably cause the effective injection efficiency to increase.

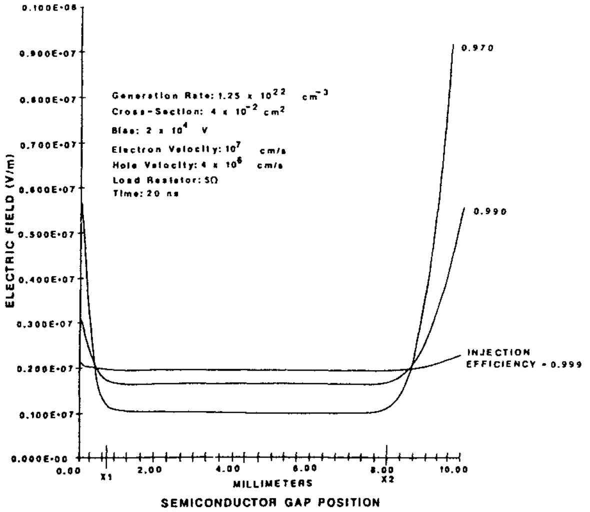


Figure 5. Representative Electric Field Profiles Generated by Computer Model.

Other examples and results of the analysis, as well as a detailed comparison of the experimental and theoretical waveforms, are planned.

Experimental Results

All switches were tested in a line pulser circuit similar to that shown in Figure 6. Parameters which were varied were the pulse width of the PFN and the circuit impedance. This simple circuit can be used because GaAs switches can be DC biased for up to several minutes, unlike Silicon in which thermal generation of carriers will cause the switch to conduct within microseconds. Response of the Nd:YAG activated switch was obtained by measuring the switch current with a Pearson No. 411 current transformer. The response of the laser diode activated switch was obtained by measuring the current pulse in the discharge loop with a Tektronix CT-1 current transformer. The waveforms were acquired with a Tektronix 7912AD programmable digitizer and displayed and processed on a Tektronix 4052 microcomputer.

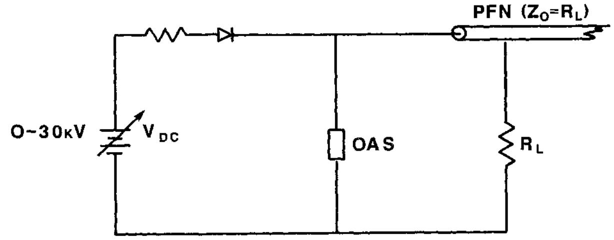
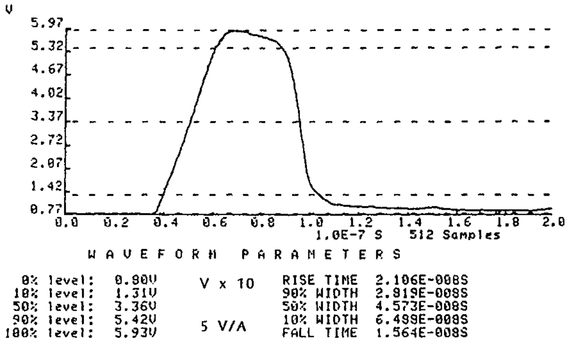


Figure 6. Test Circuit for Photoconductive Switch



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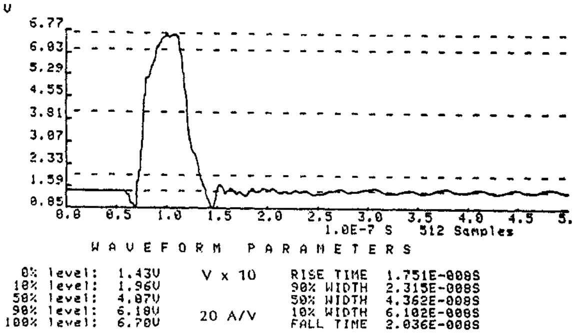
         W A V E F O R M   P A R A M E T E R S

  0% level:  0.80V    V x 10   RISE TIME  2.106E-008S
 10% level:  1.31V             90% WIDTH  2.819E-008S
 50% level:  3.36V             50% WIDTH  4.573E-008S
 90% level:  5.42V             10% WIDTH  6.499E-008S
100% level:  5.93V    5 V/A    FALL TIME  1.564E-008S
```

Figure 7. Laser Diode Controlled Switch Response

The waveform in Figure 7 represents a typical response of a laser diode controlled Cr:GaAs switch. The PFN was charged to 2 kV and the switch, which had a 1mm gap length, illuminated with a 55 ns laser pulse of approximately 600 watts peak. The risetime and 50% pulsewidth of the current pulse are 21 ns and 46 ns as shown. The voltage amplitudes are shown attenuated 10X. The CT-1 generates 5 volts/amp so the peak current is approximately 10.25 amps. The PFN and load resistances are both 50 ohms so the minimum switch resistance, obtained from the observed peak current is found to be 95 ohms. This waveform was taken at a PRF of 100 Hz. Switch lifetimes of up to 1.5 million shots have been documented with no degradation of switch performance.

Figure 8 shows a typical response of a Nd:YAG laser activated GaAs switch. The PFN was charged to 20 kV and the 5mm long switch illuminated with a 25 ns laser pulse having an energy of 20 millijoules. The laser was run at a PRF of 1Hz. The PFN and load resistances in this case are both 10 ohms. The current transformer puts out 0.05 V/A when terminated into 50 ohms and a 10X attenuator was used. Applying these scale factors to the output pulse (Fig. 8) gives a peak current of 1054 amps. Given the error limits of the test circuit and measurement system, it is best determined that the minimum on-state resistance of the switch is much less than 1 ohm. This low on-state resistance may seem surprising, especially in view of the fact that the photon energy (at a wavelength of 1.06 microns) is substantially less than the band gap energy of GaAs. The explanation is probably connected with the numerous defects ($> 10^{17}/cm^3$) present in GaAs. These defects give rise to intermediate energy levels which allow for transitions to the conduction band even at optical wavelengths considered to be longer than optimum for GaAs. The risetime and pulsewidth of the switched pulse are 17 ns and 43 ns as shown. While lifetests have yet to be run in this configuration, all switches tested have endured several hundred shots.



```
         W A V E F O R M   P A R A M E T E R S

  0% level:  1.43V    V x 10   RISE TIME  1.751E-008S
 10% level:  1.96V             90% WIDTH  2.315E-008S
 50% level:  4.07V             50% WIDTH  4.362E-008S
 90% level:  6.18V             10% WIDTH  6.102E-008S
100% level:  6.70V    20 A/V   FALL TIME  2.036E-008S
```

Figure 8. Nd:YAG Laser Controlled Switch Response

Conclusions

Significant improvements in optically controlled switches have been achieved through the use of a higher powered laser diode array, the LDT-391. These results indicate that it is feasible to design a compact, highly efficient, laser diode activated bulk semiconductor power switch. With laser and switch optimally designed for each other, switches appear capable of voltages up to 10 kV DC, at currents up to 100 amperes, with on-state resistances of less than 1 ohm, and with PRF's up to 100 kHz. The Nd:YAG controlled switch is suitable for switching applications involving much higher power. Its switching speed, pulse width and PRF are limited only by the laser. Q-switched Nd:YAG lasers are available which supply sufficient energy per pulse to close a switch designed to hold off hundreds of kilovolts and switch tens of kiloamps. Development of a computer code which describes the transient conductivity and electric field profiles in the switch is progressing satisfactorily. The analysis has contributed to the understanding of the switch, particularly with regard to the effect of non-ohmic contacts.

Acknowledgments

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