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Subnanosecond, High Voltage Photoconductive Switching in GaAs

Robert L. Druce, Michael D. Pocha, and
Kenneth L. Griffin
Lawrence Livermore National Laboratory,
Livermore, CA

B. Jim O'Bannon
Rockwell International, Anaheim, CA

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Robert L. Druçe, Michael D. Pocha, Kenneth L. Griffin

Lawrence Livermore National Laboratory
Livermore, California 94550

B. Jim O'Bannon

Rockwell International
Anaheim, California 92803-3170

ABSTRACT

We are conducting research on the switching properties of photoconductive materials to explore their potential for generating high-power microwaves (HPM) and for high rep-rate switching. We have investigated the performance of Gallium Arsenide (GaAs) in linear mode (the conductivity of the device follows the optical pulse) as well as an avalanche-like mode (the optical pulse only controls switch closing). Operating in the linear mode, we have observed switch closing times of less than 200 ps with a 100 ps duration laser pulse and opening times of less than 400 ps at several kV/cm fields using neutron irradiated GaAs. In avalanche and lock-on modes, high fields are switched with lower laser pulse energies, resulting in higher efficiencies; but with measurable switching delay and jitter. We are currently investigating both large area (1 cm^2) and small area (< 1 mm^2) switches illuminated by AlGaAs laser diodes at 900 nm and Nd:YAG lasers at 1.06 μm.

1. INTRODUCTION

Photoconductive switches hold great promise for switching high voltages and high currents on time scales substantially less than one nanosecond.[1] These switches offer several advantages over commonly used pulse power switches. Since carriers are generated directly by photon absorption, the turn-on time of the switch in linear mode is determined directly by the laser pulse, resulting in virtually no jitter in the switch. Laser control also provides an optically isolated trigger, allowing convenient stacking of devices for high voltage operation and paralleling devices for high current operation. Therefore, these devices can easily be packaged to switch high voltage and current. With the very short pulse lasers available today, rise times can approach picosecond time scales. Linear photoconductive switches are also one of the very few opening switches available at high voltages. However; linear operation is not possible at high fields. As the open-state field on a GaAs switch is increased above a threshold value, the switch will close as in linear mode. The switch will not recover, however, until the applied field across the device is reduced; allowing the device to be used as a fast closing switch but not as an opening switch. These characteristics (fast closing, no jitter, fast opening) combine to make linear/lock-on photoconductive switches one of the very few known candi-

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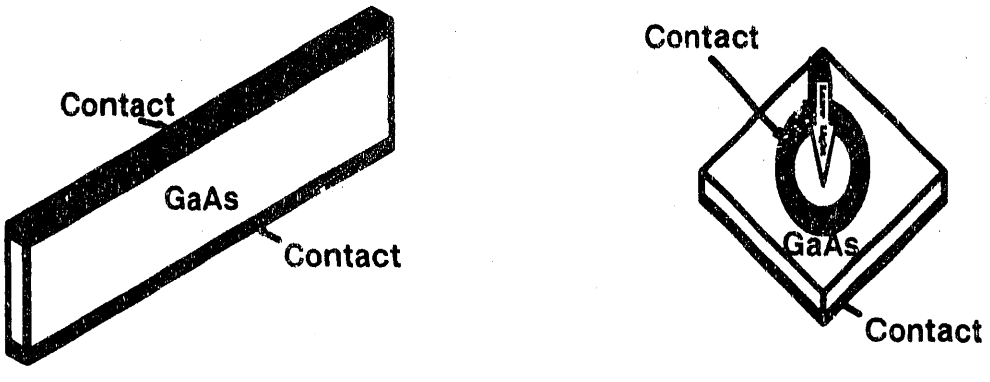
dates for direct microwave generation in the 500 MHz – 3 GHz region. Our work in linear and lock-on photoconductive switching is concentrating on generating pulses and microwave waveforms in the 1 – 2 GHz region. At high fields across the switch, avalanche mode of operation can be used to combine the advantage of optical trigger isolation with high switch gain (small trigger energy required to switch large energies). In avalanche operation, the closing time of the switch is determined by the physics of the switch and is often slower than in linear or lock-on modes. Recovery times in all three modes of operation is less than 100 ns, allowing repeated operation at repetition rates approaching 10 MHz.

2. THREE MODES OF OPERATION

The phenomenon of photo-induced conductivity is quite simple in concept. A photon is incident on a semiconductor whose ionization energy is less than the energy of the photon. The photon is absorbed, releasing its energy to the semiconductor crystal structure, ionizing an atom and releasing an electron-hole pair. The electron and hole are now free to be accelerated by an applied field and participate in the conduction process. GaAs is a direct band-gap semiconductor with a band gap of 1.43 eV, which corresponds in photon energy to a wavelength of about 860 nm. At wavelengths shorter than 860 nm absorption will be very strong. This strong absorption leads to a very short absorption depth (several micrometers). The very short absorption depths lead to very shallow conduction channels at the surface of the crystal and very high current densities. If the crystal were perfect there would be no absorption at wavelengths longer than the wavelength corresponding to the band gap. In reality, the crystal is not perfect and there is absorption at wavelengths longer than the band gap wavelength at impurity sites and other crystal defect sites. This extrinsic absorption can be used to advantage to create deeper conduction channels and a corresponding decrease in current density. Once the carriers are generated, the forces due to the field across the device accelerate the carriers toward the electrodes. Collisions with the crystal structure scatter the electrons and holes, limiting the velocity in the field direction. This scattering gives rise to the mobility. The carrier velocity varies linearly with field at low field values; hence, the mobility is a constant value at low fields. As the field is increased, there is a region in which the velocity actually decreases as field increases. At even higher fields, the velocity saturates and the current is essentially independent of field until avalanche breakdown occurs. As a result of this complicated mobility curve in GaAs, the resistance of a linear photoconductive switch depends in a complicated fashion on the open-state field across the switch and the laser energy absorbed by the switch. In general linear/lock-on mode switches require fairly high laser intensities (several MW/cm^2) to switch successfully at high fields. In linear mode, after the laser light is removed from the switch, recombination works to remove the carriers from the conduction process. The recombination time of GaAs can be made as short as several picoseconds with the proper preparation, giving switch opening times of tens or hundreds of picoseconds. As the field is increased beyond a threshold value, the switch will only partially recover, leaving the device in a partially open state. This partially open state has been labeled "lock-on" by researchers at Sandia National Laboratory, Albuquerque[2] and will be used here also. The physics of this state is not well understood at this time but efforts are under way at LLNL to improve our understanding.[3,4] It has been noted that the lock-on field (between 4 and 8 kV/cm) is on the same order as the field at the peak in the carrier velocity curve. The practical implication of lock-on is that the linear switch can be used as a fast opening switch at low fields (below several tens of kV/cm, depending on device preparation) but becomes a fast closing switch at higher fields. If the laser pulse energy is reduced with high fields across the switch, another aspect of the lock-on phenomenon is seen that we have labeled "avalanche" mode. A low-energy laser pulse absorbed by a GaAs switch biased to a high field will produce a small electrical pulse, limited by velocity saturation in the switch. After a finite delay, the device will go into a highly conductive state, as though the material were experiencing avalanche breakdown. However; the lowest average field at which this "breakdown" occurs is almost an order of magnitude lower than the intrinsic breakdown field of GaAs. It has been theorized that Gunn domains increase the localized fields sufficiently to cause avalanche. Modeling at LLNL indicates that, while possible, Gunn domains are an unlikely mechanism for avalanche operation. Work by Mazzola[5] (confirmed by White at LLNL) indicates that trap filling by double charge injection may explain avalanche operation. Further work is required to determine conclusively the mechanism of avalanche mode.

3. EXPERIMENTAL SETUP

Our work at LLNL is concentrating on photoconductive switch operation on subnanosecond time scales, requiring careful attention to circuit design and diagnostic development. We have been conducting experiments using two geometries. Figure 1 shows diagrams of the two geometries. The slab geometry was chosen to facilitate device testing in a minimum inductance circuit (see Fig. 4) at high voltage. The doughnut switch has a long surface path to optimize surface flashover and small size to allow control with a laser diode through a fiber optic. The dimension of the switch in the field direction is typically 5 mm for the slab switch and 500 μm for the doughnut switch. The switch is pulse biased by a pulse with an amplitude of 1 – 50 kV with the wave shape shown in Fig. 2. Figure 3 is a block diagram of the experimental setup used to test the switching parameters of GaAs and InP. The timing and diagnostic chain are identical for both slab and doughnut switch tests. The test fixture and, possibly, the laser change between the two geometries. The Nd:YAG laser is a Quantel YG501-30. This passive mode-locked laser produces a 100 ps pulse with total pulse energies up to 50 mJ/pulse at $\lambda = 1.06$ μm with a repetition rate of 30 Hz. The beam is expanded onto the slab switch with a set of cylindrical lenses; the beam is purposely made larger than the switch to ensure reasonably uniform intensity over the area of the switch. We do not use a homogenizer; The benefits of beam uniformity may be overshadowed by temporal degradation of the laser pulse by the homogenizer. In addition, the homogenizer adds significant loss to the optical system. When the Nd:YAG laser is used to illuminate the doughnut switch, the beam is focused onto the fiber. All digitizers and oscilloscopes are triggered directly from the optical output of the laser to minimize jitter (jitter in the diagnostic system is about 250 ps). All fast signals are transmitted from the test fixture to the recorders with a combination of Suhner Sucoflex and Andrew RF19 foam dielectric cables and are recorded on Tektronix 7250 digitizers. The overall bandwidth of the diagnostic system is limited by the



a. "Slab" geometry

b. "Doughnut" geometry

Figure 1. Diagrams of the two switch geometries used in our switching studies.

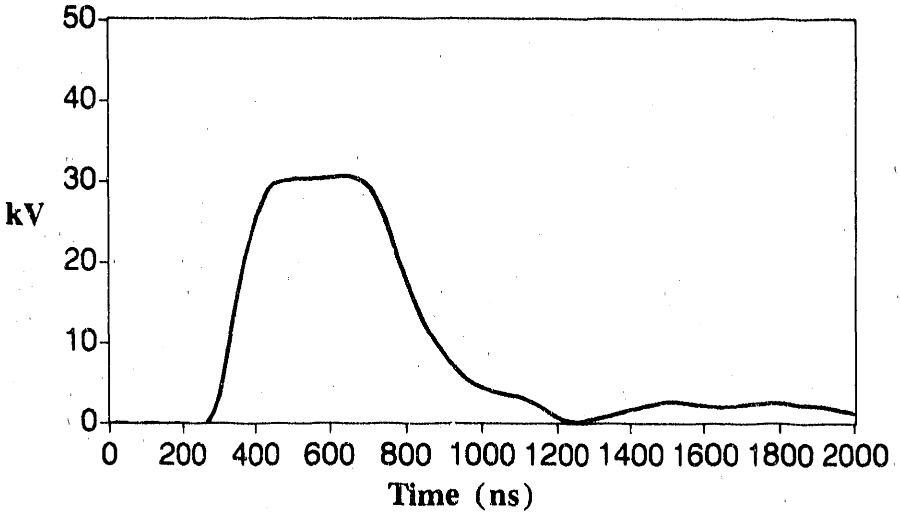


Figure 2. A representative charge pulse showing pulse shape and duration.

interconnecting cables to about 2 GHz. Laser peak intensity, pulse shape, and total pulse energy are monitored by an LLNL designed photo-detector and a Laser Precision RJ-7000 optical energy analyzer. Fault current through the switch is limited by a series resistor (nominally 100 Ω for the slab switch and 600 Ω for the doughnut switch) and the actual voltage applied to the switch is monitored by a 100:1 resistive voltage divider. All high voltage components are fully shielded (including the switch test fixture) to minimize electromagnetic interference. All digitizers and oscilloscopes are in a screen room to further increase dynamic range. Details of the slab transmission line test fixture are shown schematically in Fig. 4. The line dimensions are 2 cm wide, 0.5 cm spacing (the average field is twice the voltage), and 1 m length, giving a characteristic impedance of approximately 100 Ω and an electrical length of about 3 ns. It should be noted that the switch shorts the transmission line in the axial center and pulses are propagated in both directions from the switch, giving an effective switched impedance of 50 Ω. The switch is mounted in a demountable insert to allow for simple mounting in the line fixture and easy modification of the switch mounting. The entire slab switch transmission line fixture is enclosed in a pressure vessel with a 50 psig capability to facilitate pressurization to enhance open state voltage hold off. There are a total of six *in situ* fast pulse diagnostics in the test fixture. There are four capacitive dividers and two $\dot{B}$ probes with positions indicated in Fig. 4. The physical area of the $\dot{B}$ probe is about $10^{-3} cm^2$; the effective area is somewhat less. The capacitive and $\dot{B}$ probes have bandwidths greater than 4 GHz. The *in situ* pulse diagnostics (capacitive dividers and $\dot{B}$ probes) were calibrated with a known pulse. A block diagram of the test fixture for the doughnut switch is shown in Fig. 5. The laser diode used to control the switch is an AlGaAs device from Laser Diode, Inc. rated at 70 W peak power. We operate the laser at peak power of about 10 W and 5 ns duration pulses, giving pulse energies of about 20 - 50 nJ. The switch area can be immersed in dielectric fluid (typically Fluorinert or equivalent). The output of the line is connected directly to coaxial cable, which is attenuated with Barth attenuators to drive the 7250 digitizers. The recorded signal corresponds to the current through the switch multiplied by the load impedance. The charged side of the microstrip is also connected to 50 Ω coaxial cable, allowing adjustment of the pulse length to arbitrary values. The switch is mounted in a small switch carrier that is connected to the microstrip line by two flea clips. The bottom side of the switch is connected directly to the switch carrier by silver loaded epoxy or indium solder. The top side of the switch is electrically

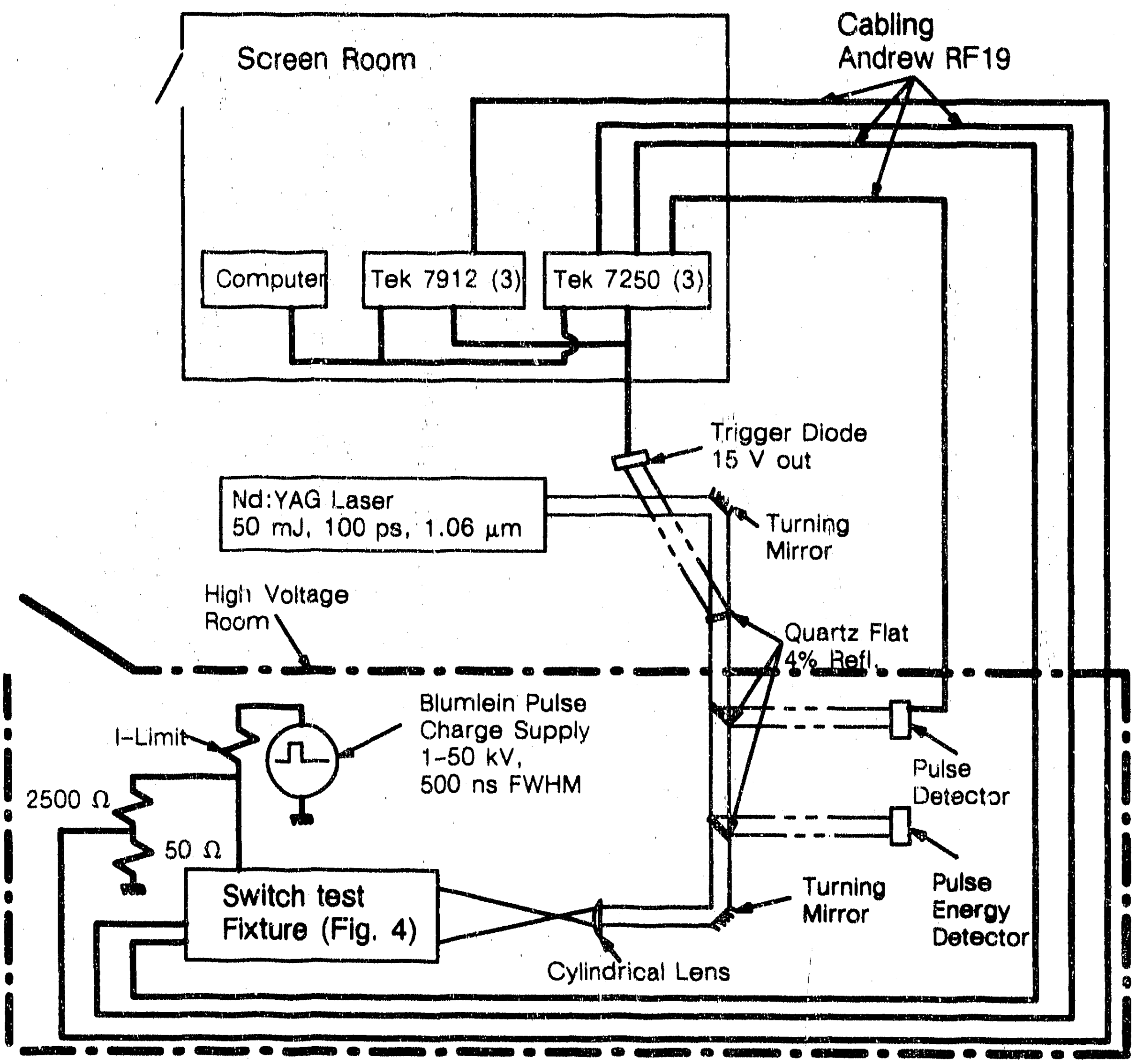


Figure 3 Block diagram of the laboratory setup used to research switches.

connected to the circuit by two small wire loops connected from the doughnut across a small gap in the carrier to the output side of the carrier.

4. EXPERIMENTAL RESULTS

There are four main issues we are studying concerning photoconductive switching: open-state voltage holdoff, attainable closing and opening switching speed, efficiency of laser control and device life.

4. 1. Open state field

The theoretical bulk breakdown field for GaAs is 200 kV/cm. In realizable switch configurations, the attainable open-state field is limited by surface flashover of the GaAs. Figure 6 shows graphically the maximum attainable field results to date. There are two ways to improve surface flashover: shape the field away from the surface or improve surface preparation. We are using both methods to improve the open-state field attainable with these switches. Our investigations have shown that, with no field shaping, the slab switch tends to flash over near the end in

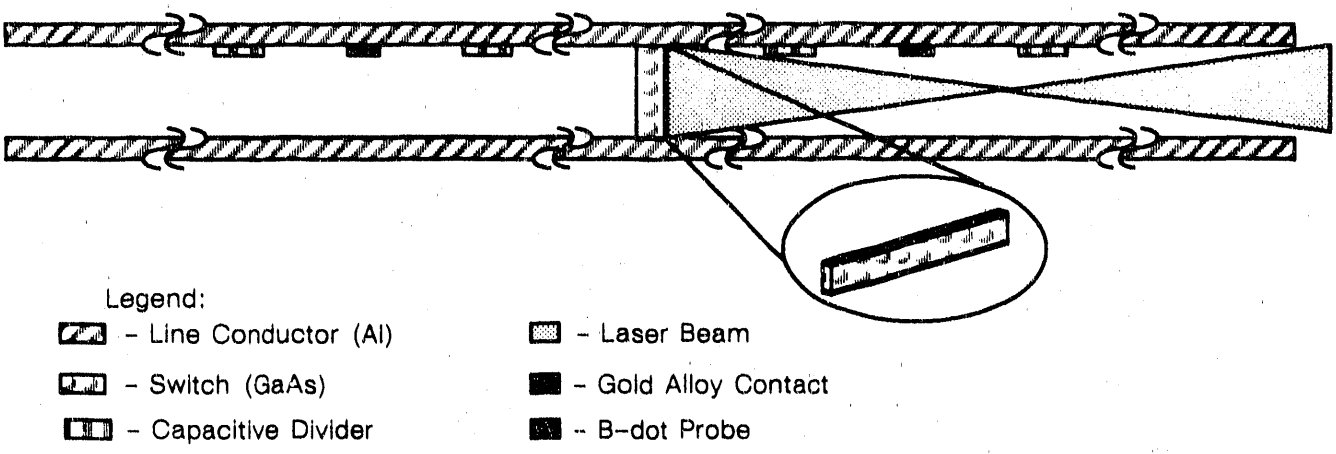


Figure 4. Block diagram of parallel plate transmission line test fixture used to test slab switch.

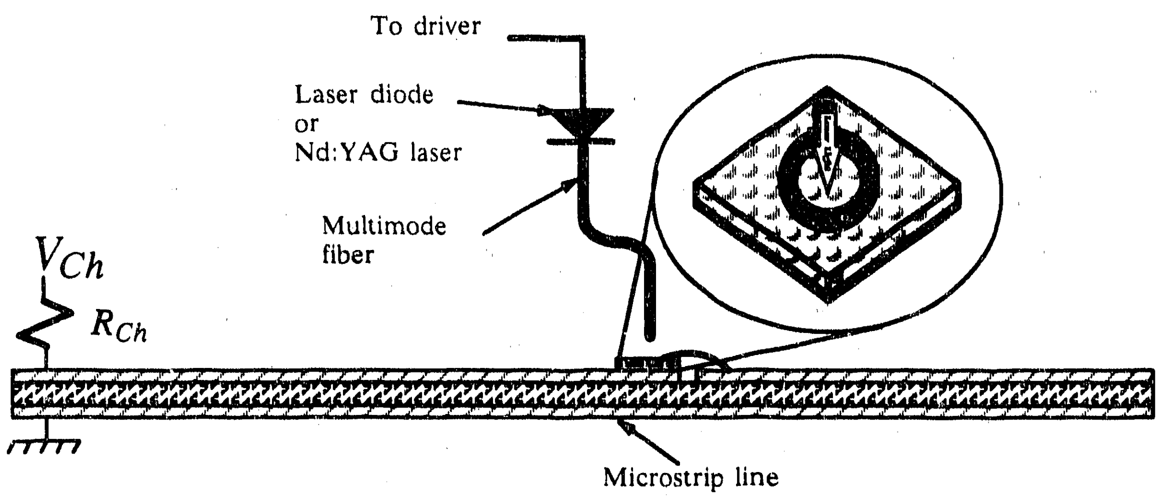


Figure 5. Block diagram of microstrip transmission line test fixture used to test doughnut switch.

the high field region. To alleviate this problem, the switch carrier was modified to shape the fields away from the surfaces that were not illuminated by the laser. Since the triple junction (where the GaAs, aluminum, and insulating gas meet) is usually the point at which a flashover initiates, we are also attempting to embed the electrodes in the GaAs to relieve the fields at the triple junction along the illuminated face of the slab switch. One of the primary design goals of the doughnut switch is reduced field on the surface of the device by extending the surface path length. The doughnut switches routinely attained average fields of over 150 kV/cm, demonstrating that surface flashover is an issue. Another area of research is surface coatings. Many insulating materials that can be used to coat the semiconductor have been shown to hold fields of > 200 kV/cm in SF_6. Coating with some of these materials improves the surface flashover properties of GaAs by varying amounts. Polyimide has shown the greatest improvement overall. Coated slab samples operate as reliably in atmospheric SF_6 as in pressurized SF_6 (this is not true of uncoated sam-

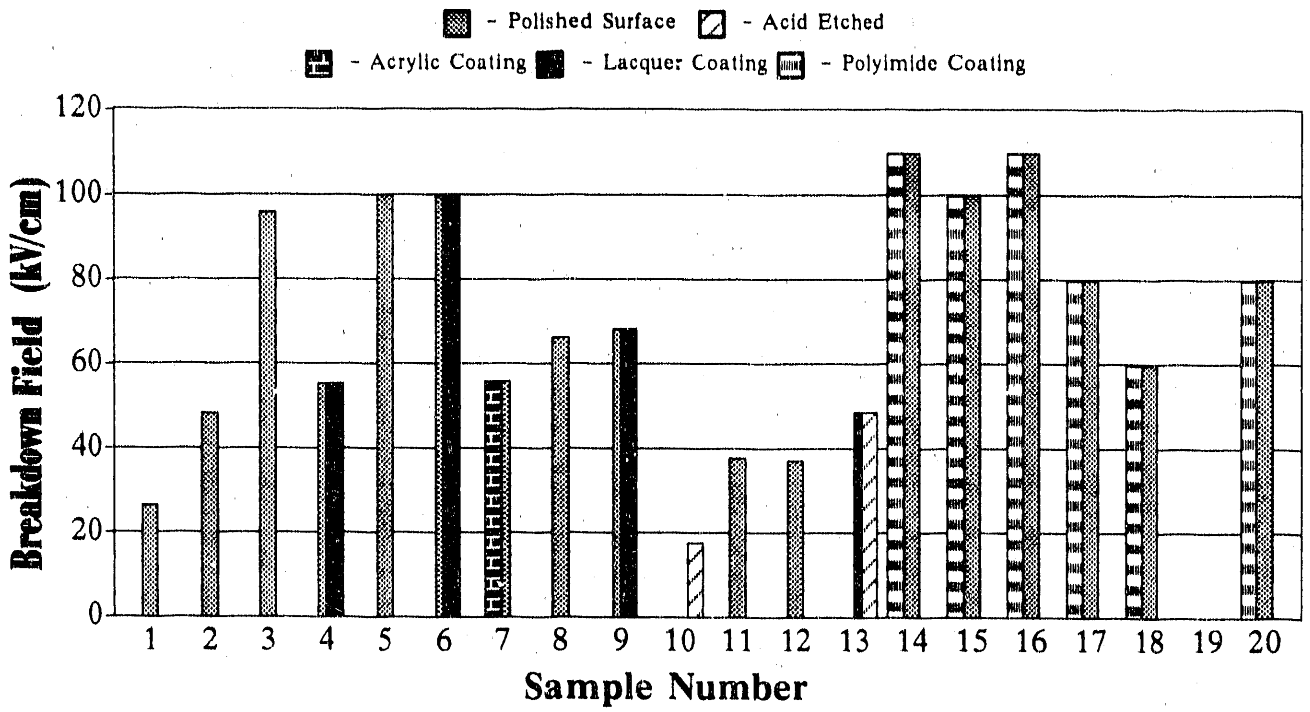
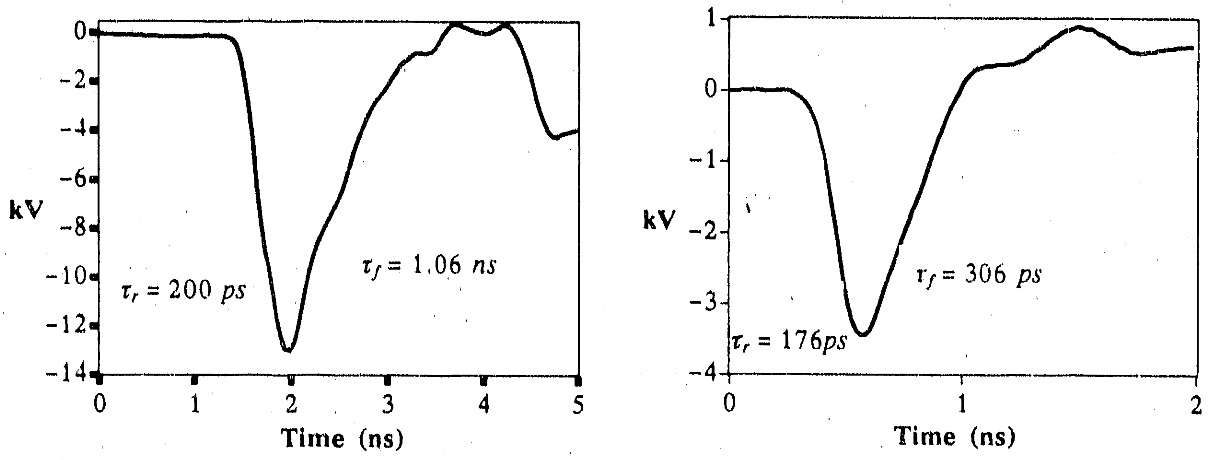


Figure 6. Plot of dark breakdown field for several samples.

ples). As a result, the coatings also relax the requirement for a pressure vessel. Doughnut devices are normally coated with epoxy (primarily to improve mechanical strength) or left uncoated. Semiconductor materials in general and GaAs in particular exhibit variability of the semiconductor material. Several samples of GaAs prepared in exactly the same manner may have maximum attainable open state fields that differ by as much as an order of magnitude. We are studying uniformity of surface preparation to alleviate quality assurance difficulties with the GaAs wafers.

4. 2. Switching studies, linear/lock-on

Three material types have been studied to date: semi-insulating LEC grown GaAs, Fe doped InP, and neutron irradiated LEC grown GaAs. While somewhat similar, each material behaves in a unique fashion. Figure 7 shows representative pulses for the LEC grown and neutron irradiated, LEC grown GaAs switching experiments showing general pulse shape and typical time scales. The bias voltage for these shots was below the threshold for lock-on. Figure 8 shows a pulse for a charge well above the lock-on threshold for LEC GaAs. It can be seen in Fig. 8 that the closing time of the switch has not been significantly affected at higher field levels in lock-on mode but that the switch no longer fully opens. Lock-on seems to be related only to the field across the switch (we have also seen similar lock-on fields in the doughnut geometry). Other researchers have also seen lock-on[6] in direct band gap semiconductors. The lock-on field (4 - 8 kV/cm) left on the switch at long times indicates high power dissipation in the switch. This high dissipation may reduce switch life. LEC GaAs has the highest gain (ratio of output electrical power/energy to laser power/energy) in lock-on mode with a value of about 9 at fields of 70 kV/cm (without correcting for losses due to reflection). Comparing the data also indicates that the gain of the switch is related to the recombination time of the material. This result is not surprising since faster recombination will remove carriers from the conduction process faster. The mobility of the material may also be degraded by increased scattering from recombination centers in neutron irradiated devices. The absorption depth for the LEC GaAs we use has been measured at ≈ 4 mm. We estimate that approximately 10% of the light incident on the 1 mm thick switch is ab-



a. LEC GaAs, charge voltage ≈ 12 kV, Laser energy ≈ 1.32 mJ.

b. Neutron irradiated LEC GaAs, charge voltage ≈ 12.4 kV, laser energy ≈ 227 μJ

Figure 7. Typical LEC GaAs and neutron irradiated LEC GaAs shots below lock-on threshold.

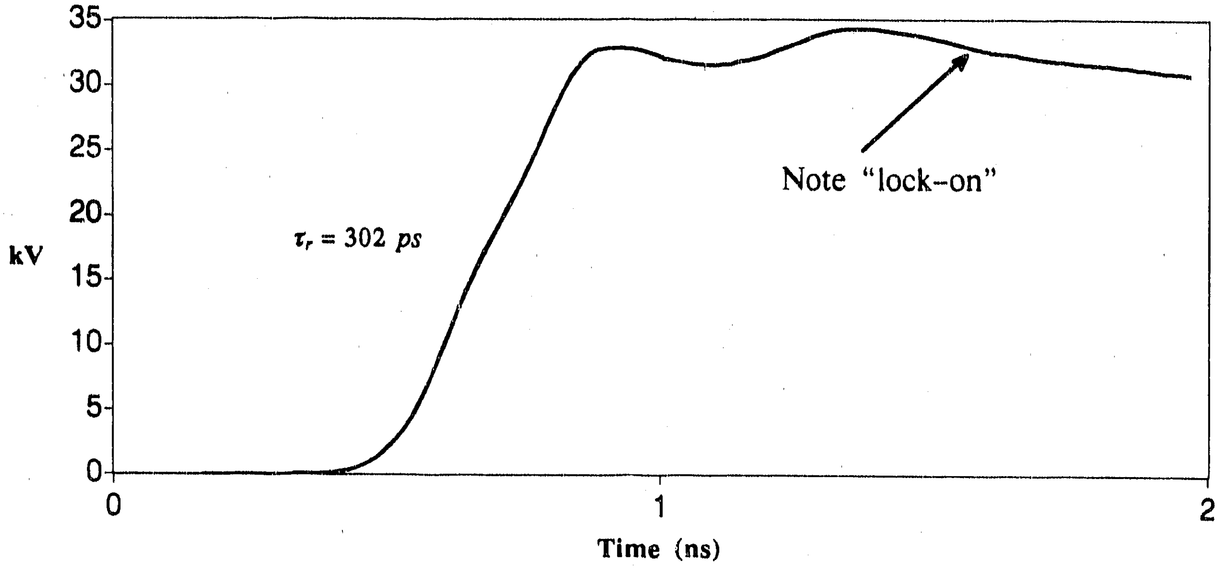


Figure 8. Plot of lock-on semi-insulating GaAs switch behavior, charge voltage ≈ 35 kV, laser energy ≈ 2.1 mJ

sorbed. We tested two and three 1 mm thick switches stacked in the direction of laser propagation. Figure 9 shows the result. It is seen from Fig 9 that two switches provide about twice the gain as one switch but that three switch do not provide three times the gain. This reduced gain may be due to interference patterns at the switch interfaces. We are fabricating 2 mm thick switches with an anti-reflection coating on the laser side and a reflective coating on the back side to improve overall absorption further. We believe that high-field power gain can be improved to 16 – 20 using these methods.

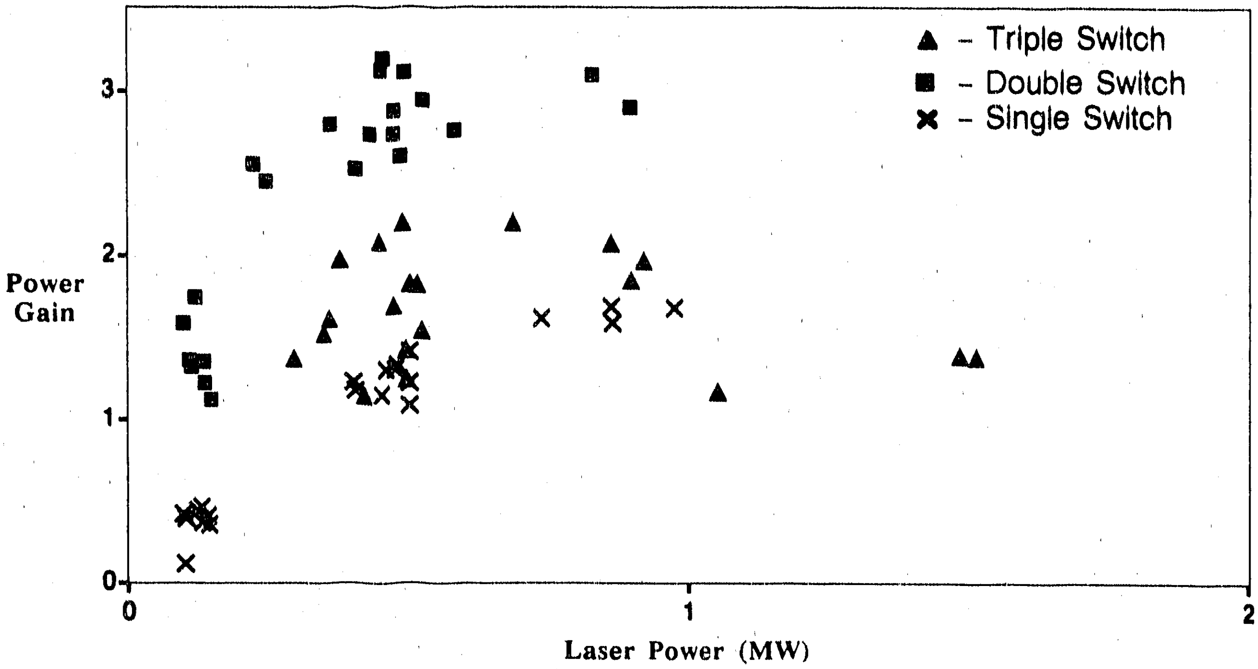
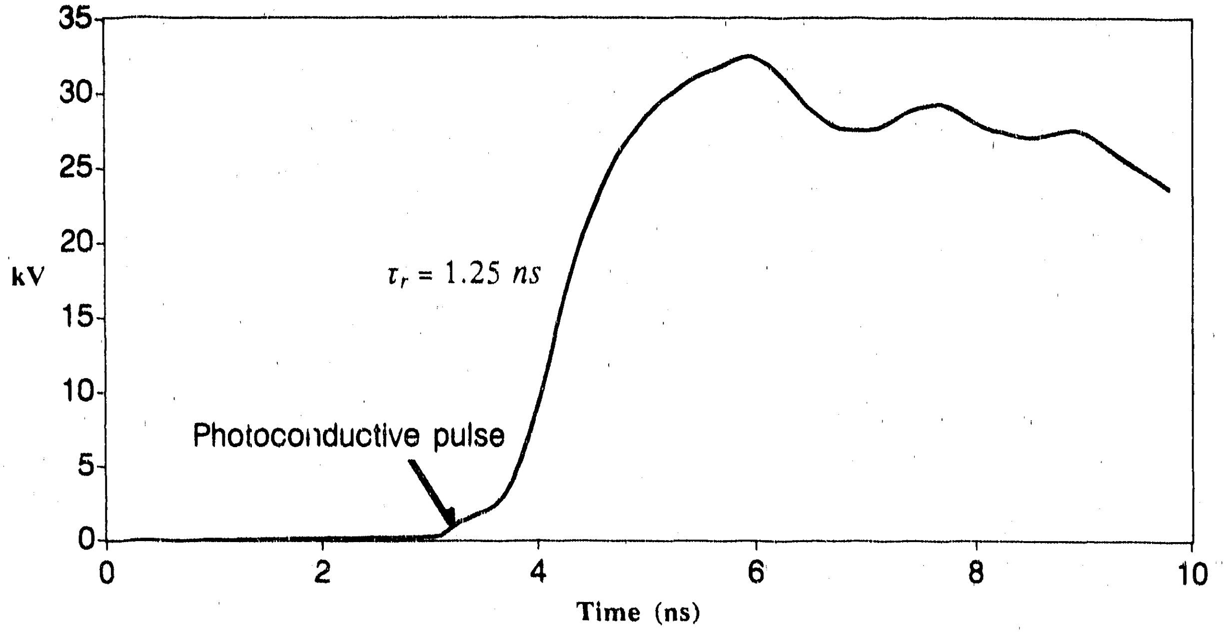


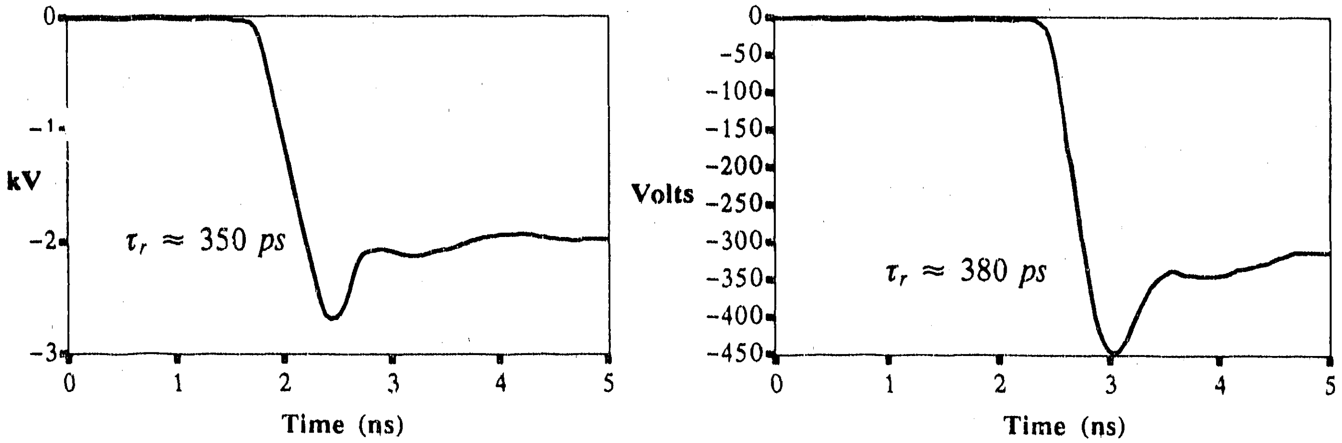
Figure 9. Comparison of switch gain with multiple switches stacked in the direction of laser propagation.

4. 3. Switching studies, avalanche

The major drawback of linear photoconductive switching is the low switch gain achievable. Operation of the switch with all of photoconductive switching's advantages plus gain multiplication would be very attractive indeed. We are operating switches at high fields to study carrier multiplication by the field in avalanche mode. Intrinsic dark breakdown occurs in GaAs at about 200 kV/cm. We have discovered that conductivity multiplication can be photo-induced at even lower fields (as low as 25 kV/cm). Figure 10 shows typical examples of waveforms produced in avalanche mode. Figure 10a is a typical waveform for the slab geometry. Figure 10b is a typical waveform for the doughnut geometry triggered by the diode laser. Figure 10c is a typical waveform for the doughnut geometry triggered by the Nd:YAG laser. It is interesting to note that the waveforms in Figs. 10b&c are very similar even though the conditions are very different. Figure 10b is triggered by the laser diode, which has an absorption depth shorter than the depth of the doughnut switch (we have not measured the absorption depth exactly) and a laser rise time (about 1 ns) longer than the closing time of the switch. Figure 10c is triggered by the Nd:YAG laser, which has an absorption depth longer than the depth of the doughnut switch (≈ 4 mm) and a rise time shorter than the closing time of the switch (< 100 ps). It should also be noted that the wave shapes are very similar even though charge and output voltages are very different. There are delay and jitter associated with avalanche switching. A systematic study was undertaken to determine the rise time, delay, and jitter as a function of field and laser energy. We found that there is a threshold for avalanche mode of about 20 - 25 kV/cm. Below 25 kV/cm average field, switching becomes very erratic and delay times to avalanche become long (many 10's or 100's of ns). We found the rise time of the avalanche mode - ≈ 350 ps for the doughnut, ≈ 1.25 ns for the slab - to be essentially independent of laser energy and very weakly dependent on charge voltage from avalanche threshold to maximum reliable switching level, which is about 160 kV/cm open-state field. Delay and jitter are dependent primarily on open-state field. Delay changed with open-state field from several 10's of ns (50 ns or more) near avalanche threshold to ≈ 500 ps at fields of 60 kV/cm or greater. Jitter changed with open-state field from 10 - 20 ns at avalanche threshold to less than 1 ns (approaching the jitter of the diagnostic system) at high fields. The fact that avalanche mode occurred reliably with uniform illumination of the switch at high laser energies (approaching mJ levels) was initially puzzling to us since



a. Slab geometry, charge voltage ≈ 35 kV, laser energy ≈ 100 μJ.

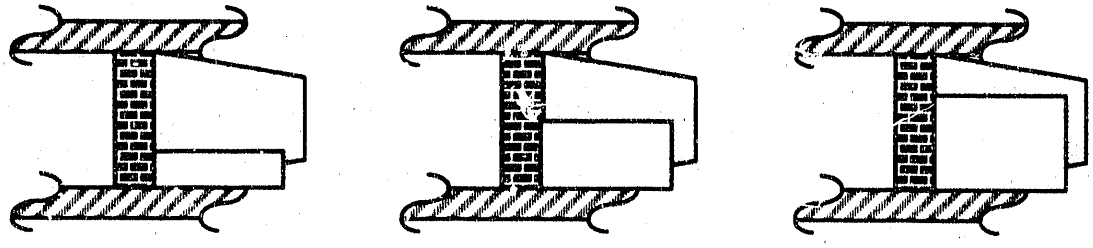


b. Doughnut geometry, charge voltage ≈ 5 kV, laser energy ≈ 25 nJ; AlGaAs diode laser

c. Doughnut geometry, charge voltage ≈ 800 V, laser energy ≈ 10 μJ; Nd:YAG laser

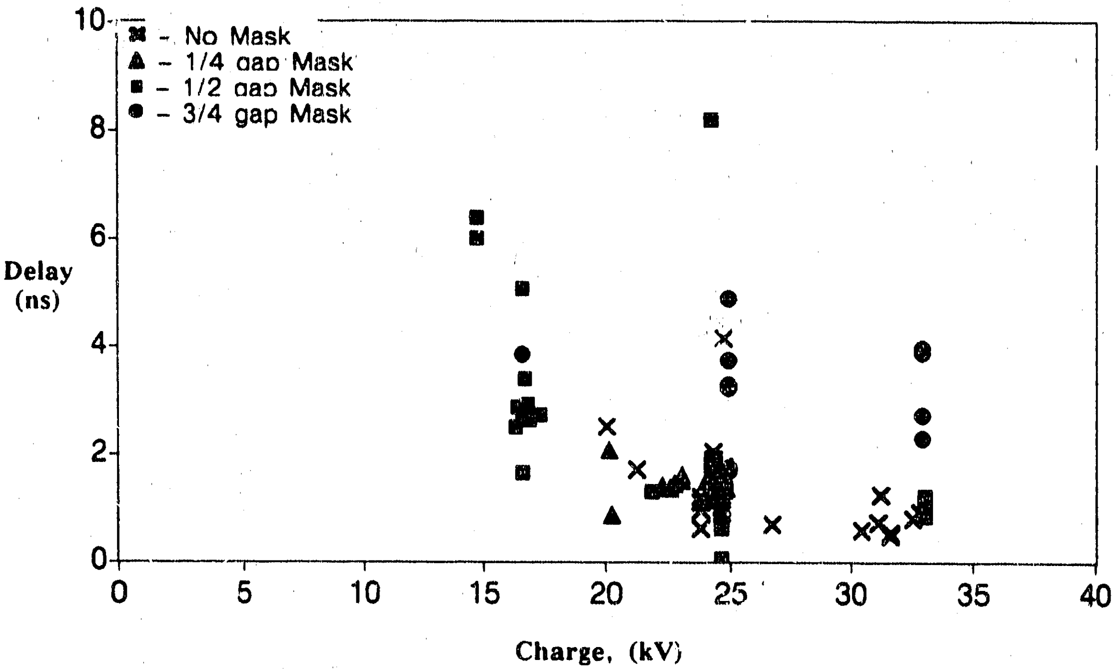
Figure 10. Comparison of typical avalanche waveforms for LEC GaAs in slab and doughnut geometries.

the field across the switch will actually be reduced by photoconduction at these high laser energies, reducing the probability of avalanche multiplication of carriers. The trap-filling theory better explains this behavior. To determine geometry effects, the laser was shadowed as shown in Fig. 11. Figure 11 shows that the shadowing has little effect unless over half of the gap is shadowed. This lack of effect is true whether the anode or cathode is shadowed. The ability to operate in avalanche mode at fields much lower than dark breakdown and the shadowing results lead us to believe that avalanche mode is not a classical avalanche effect. A residual field of 4 - 8 kV/cm similar to lock-on is also observed in avalanche mode switching, indicating that the two are related.



1/4 of gap masked 1/2 of gap masked 3/4 of gap masked

a. Diagram of masks used to shadow the switch.



b. Plot of delay between photoconductive pulse and avalanche pulse in LEC GaAs slab geometry.

Figure 11. Part b is a plot of the delay between the photoconductive pulse and main pulse as a function of charge voltage with the shadowing arrangement shown in 11a.

4. 4. Life time

Switch life time is a definite issue for photoconductive switches used to switch high powers. We have observed device life from as little as 10 shots at fields nearing 100 kV/cm to essentially unlimited life at fields below 20 kV/cm. The mechanism of switch failure is also not clear in lock-on or avalanche modes of operation. There has been obvious surface damage on some failed devices while there is no obvious damage of any kind on other devices. This damage (or lack of damage) is true at both medium and high field operation. The current densities in our devices - assuming uniform current density - have been < 5 kA/cm^2 slab devices and > 10 kA/cm^2 in doughnut devices.

5. CONCLUSIONS

It is clear that photoconductive switches have a potential place in general pulsed power switching and microwave generation in particular. Long pulses will be difficult to generate in linear mode with the short recombination time direct band gap semiconductor switches. Photoconductive switches are ideal for the direct generation of microwave pulses and waveforms, particularly in large systems where many fast switches must be synchronized. Power densities approaching 30 MW/cm^2 have been observed. Efficiency of absorption and device life are still important issues barring the way to routine use of photoconductive switches in large systems.

6. ACKNOWLEDGMENTS

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