High Gain Photoconductive Semiconductor Switching*

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I. ABSTRACT

Switching properties are reported for high gain photoconductive semiconductor switches (PCSS). A 200 ps pulse width laser was used in tests to examine the relations between electric field, rise time, delay, and minimum optical trigger energy for switches which reached 80 kV in a 50 Ω transmission line with rise times as short as 600 ps. Infrared photoluminescence was imaged during high gain switching providing direct evidence for current filamentation. Implications of these measurements for the theoretical understanding and practical development of these switches are discussed.

II. INTRODUCTION

Low-voltage, linear PCSS have properties such as picosecond rise times and jitter, gigahertz repetition rates, and lifetimes of greater than 10^{10} shots.[1-3] These switches can be scaled to handle higher powers, but their optical trigger energy requirements generally become excessive. Estimates for large applications, such as high-current, RF accelerators, give optical trigger energy requirements of several kilojoules per pulse, if linear PCSS is used.[4] Even small applications such as space based transmitters requiring only a few tens of millijoules of optical energy per pulse may not be practical with linear PCSS due to size and weight limitations. High gain PCSS are being studied to develop switches with properties similar to linear PCSS but with greatly reduced optical trigger energy requirements.

In this paper, we report switching properties and results from optical diagnostics for GaAs PCSS in a high gain switching mode called lock-on.[4-8] This switching mode is conveniently described in three phases. The "initiation phase" occurs when a switch under high field stress is activated with a short optical pulse. At low fields, only the prompt photo-response of the switch is observed as one electron-hole pair is generated for each photon absorbed. However, at high fields, carrier multiplication occurs. The evolution of the switch resistance, its subsequent rise time and delay to complete switching are a strong functions of the electric field across the switch and the optical trigger energy. Low light level initiation is an important aspect of lock-on since it allows the use of relatively small light sources for high power switching applications.

The second phase of this switching mode is called the "sustaining phase." This phase exhibits the property for which the name "lock-on" was chosen. At low fields, GaAs PCSS turn off rapidly after the initiating light pulse has ended because the carriers recombine in a few nanoseconds. At high fields, the resistance of the switch will continue to drop even after the end of the light pulse until the average field across the switch reaches a minimum. At this point, the switch will continue to conduct as long as the circuit maintains this minimum field across the switch. This is either caused by constant carrier regeneration or a change in the carrier recombination channels which greatly increases the effective recombination lifetime. The field required to sustain this switching action is called the lock-on field and ranges from 3.5 - 8.5 kV/cm depending upon material properties of the GaAs from which the switch was fabricated. In this phase, the PCSS characteristics are analogous to a Zener diode.

The third phase of lock-on is the recovery phase. When the field across the switch drops below the lock-on field, the resistance of the switch starts to recover. The time required for recovery from lock-on switching has been the subject of several papers, and circuits to minimize this time are still being studied.[9-10] Certainly, the use of lock-on PCSS for high frequency switching applications is strongly dependent on our ability to characterize and control this phase. However, this paper focuses on the first stages of lock-on and the recovery phase will not be discussed.

The relations between rise time, delay, electric field, and optical trigger energy for lock-on switching are the subject of the next section of this paper. Photoluminescence as evidence for current filamentation follow. Implications of these results are discussed from both a theoretical and practical device point of view.

III. SWITCHING PROPERTIES

The data described in this section were obtained in collaboration with research groups from David Sarnoff Research Center, Pulsed Sciences Inc., and BDM International. The individual experiments are described in more detail in other papers.[11-12] In both experiments, 1.5-cm long, lateral, GaAs PCSS were used to switch the energy stored in a 50 Ω transmission line into a second 50 Ω transmission line and load. The storage line was pulse charged to achieve high field stress across the PCSS ranging from 1 to 60 kV/cm. The switch was activated at the peak of the charging pulse by a variety of pulsed light sources with widths ranging from 50 ns to 200 ps. Properties measured were minimum trigger energy, rise time, and the delay between the prompt photo-response and the sustaining phase of lock-on as a function of the initial electric field across the switch. The fastest system used a mode locked laser to activate the PCSS and had a diagnostic bandwidth of greater than 2 GHz to measure the rise time of the pulse transmitted by the switch. An illustration of this high bandwidth is provided in figure 1 where the laser pulse (1a) and switch current below (1b) and above (1c) the electrical threshold to lock-on are shown as the switch is activated at high optical energies, approximately 20 mJ. In both cases, the switching displayed here is initiated in the linear mode and therefore the rise time of the current pulse is comparable to the width of the laser pulse, 200 ps. The difference between the two current waveforms is caused by the electric field. At 12 kV (1b) the switch recovers rapidly when the light pulse ends. However, at 30 kV (1c) the switch is above the electrical threshold to lock-on (13 kV) and continues to conduct until the energy in the storage transmission line has been transmitted.

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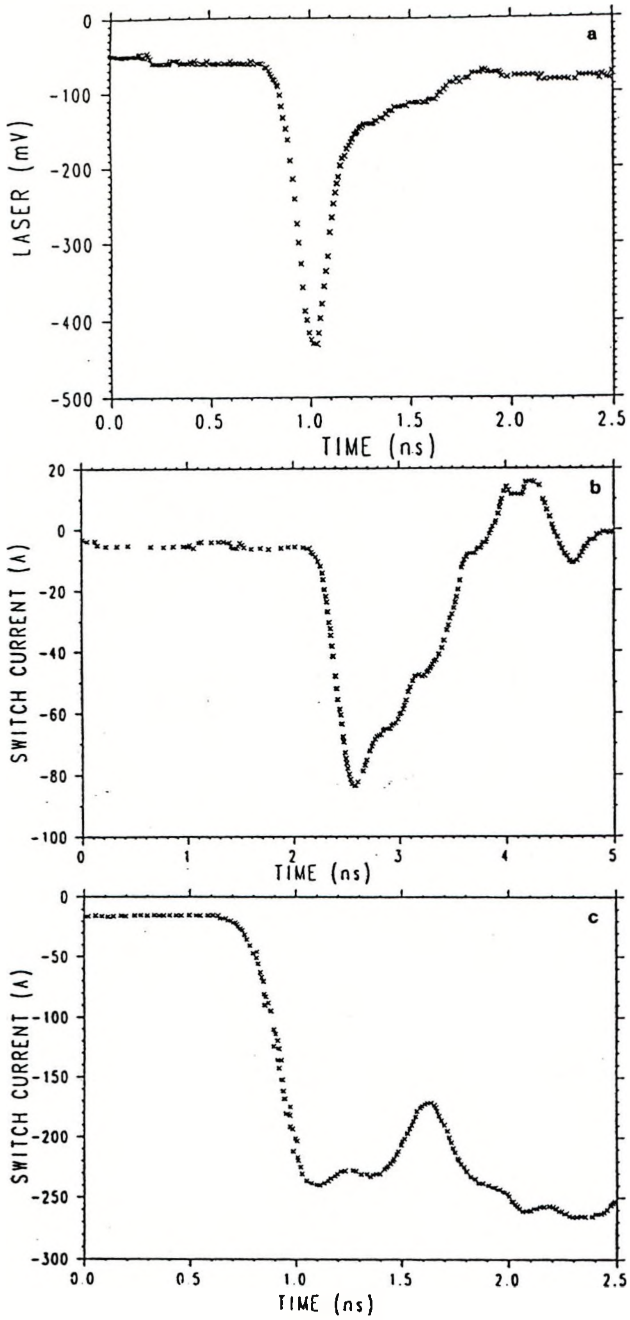

Figure 1. Linear switching is initiated in 200 ps in these examples with short laser pulses (a) of approximately 20 mJ. The switch current in waveform (b) recovers rapidly after the laser pulse has ended as the switch was charged to 12 kV which is below the 13 kV lock-on threshold. Waveform (c) shows "lock-on" following linear switching. This switch was charged to 30 kV.

The fastest rise time obtained during low light level triggering of lock-on was 600 ps (figure 2). This was achieved at approximately 80 kV using 200 μJ of 532 nm radiation in a 200-ps wide pulse. The minimum trigger energy, rise time, and delay are all inversely related to the electric field across the switch as shown in figures 3 and 4. Figure 3 gives the energy required to trigger lock-on and the associated rise times in switch current for switching obtained just above the optical threshold to lock-on. These data were obtained using a Q-switched, frequency doubled, Nd:YAG laser. Switch rise times went well below a nanosecond even though the optical pulse width ranged from 5-8 ns. Faster rise times and lower trigger energies might be achieved at even higher fields, but these switches are limited to 50-70 kV/cm by surface flashover, which causes unrecoverable damage.

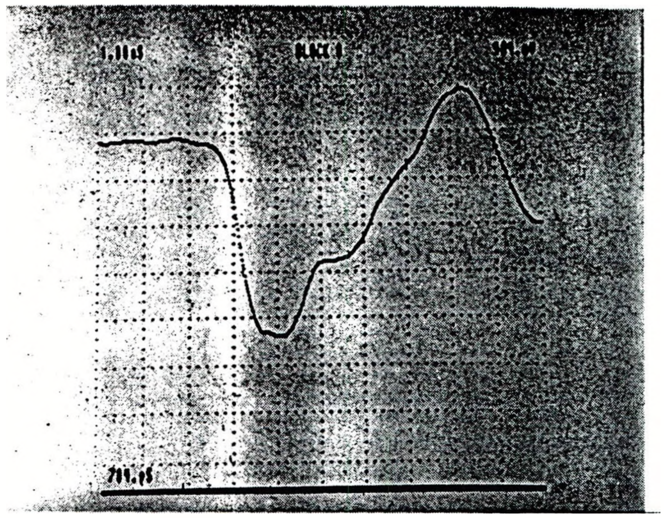

Figure 2. The fastest rise time obtained with low light level triggering of lock-on is shown this figure. Approximately 200 μJ of 532 nm in 200 ps produced this 600 ps rise time. The switch was charged to 80 kV (switch current 190 A/division vs. 1 ns/division).

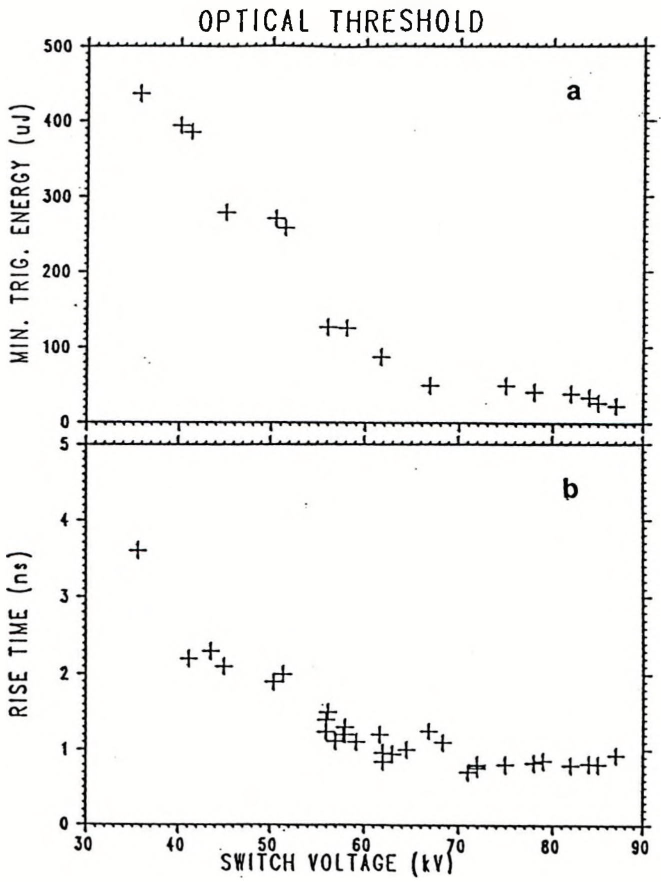

Figure 3. These data show the relations between (a) the minimum trigger energy and (b) switch current rise time as a function of the voltage across a 1.5 cm long GaAs PCSS. These measurements were taken near the optical thresholds to lock-on. Faster rise times are obtained with larger trigger optical energies.

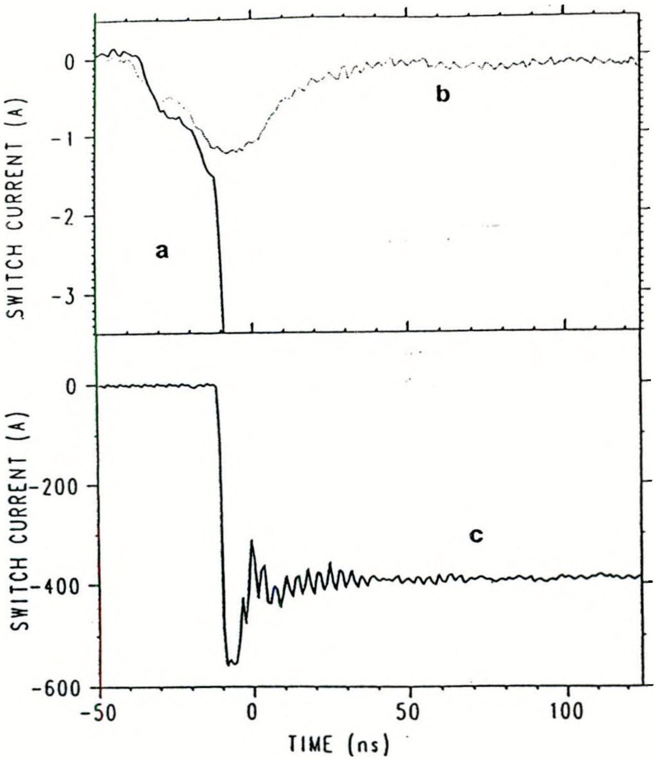

Figure 4. A short delay between the linear photo-response from low light level triggering to eventual lock-on switching is illustrated here with the switch current waveforms. The most sensitive trace (a) initially shows the shape of the previous linear shot (b). The full scale current is shown in trace (c).

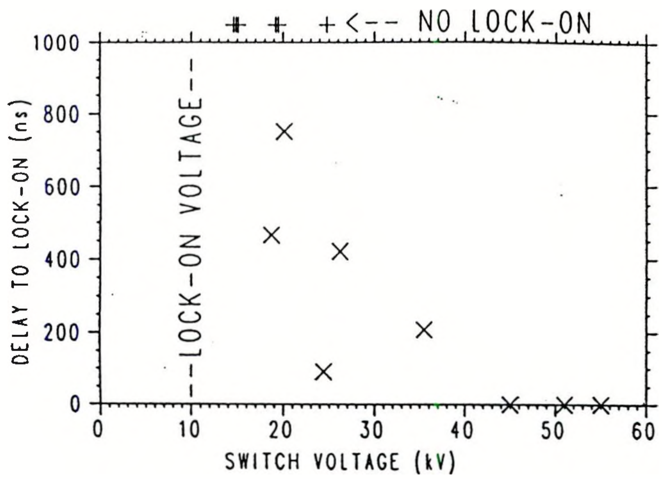

Figure 5. The delay illustrated in figure 4 is plotted here as a function of the voltage across a 1.5 cm long GaAs PCSS. The delay goes to zero (with a few nanosecond resolution) as the field across the switch increases.

The delay between the prompt photo-response of the switch and lock-on switching is the time required to initiate lock-on. Figure 4 gives and example of this delay. Figure 5 shows this delay as a function of the electric field for a PCSS illuminated with a pulsed, solid state, laser diode array (LDA). The optical pulse was about 50 ns wide with an energy of 20 μJ. The delay was measured relative to the peak of the photo-response which had the same shape as the optical pulse from the LDA. With a trigger pulse this wide, measured delays of a few nanoseconds have no significance. Near the electrical and optical thresholds to lock-on, this delay is surprisingly long. At low fields, delays as long as 750 ns were recorded. Tests which did not yield lock-on switching during the duration of the charging pulse (2 μs width) are plotted above the graph. Perhaps longer delays would have been seen if the charging pulses were longer. Despite the long delays, switch rise times are still only a few nanoseconds as shown in figure 6. At the highest fields the delay decreased to less than the laser pulse width. Meaningful measurements of small delays and rise times for lateral PCSS will be pursued with a 200 ps pulse width laser, but are not yet available. For fast rise time applications involving multiple PCSS, the delay to lock-on could lead to significant problems with jitter, even at very high fields. A sub-nanosecond study of the delay to high gain switching in vertical PCSS at higher fields has been presented by Falk.[13]

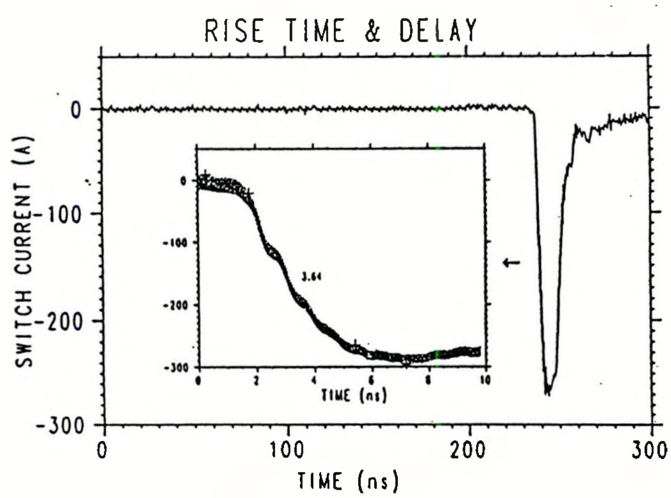

Figure 6. Shown here is the current produced by a 3.34 cm long GaAs PCSS when charged to 43 kV. A 500 ps wide, 200 μJ laser pulse triggered this switch at time zero. After a 240-ns delay, lock-on appears with a 3.6-ns rise time.

IV. PHOTOLUMINESCENCE AND FILAMENTATION

Recombination radiation has often been suggested as a possible diagnostic for the current density during lock-on. Since this radiation is strongly self-absorbed, its observation depends on the configuration of the switch. There are two basic configurations. Vertical switches have their contacts opposite one another on different surfaces of the wafer. Current is passed perpendicular to the surfaces of the wafer. Reports of bright spots of infrared radiation emanating from the ends of vertical photoconductive switches indicated the possibility of current filaments being observed from their ends.[14] Lateral switches, which have contacts on the surface of the wafer and conduct current parallel to the surface, should allow the viewing of potential current filaments from the side. The experiments discussed here were initiated as a collaboration with a Boeing Aerospace research group to image the recombination radiation which might be emitted from a lateral switch during lock-on. More results from this initial collaboration and other infrared diagnostic techniques are described in another paper.[14]

The photographs shown in figures 7 thru 9 were taken with an infrared sensitive video camera. They show the radiation pattern which is emitted from a 1-inch diameter, lateral GaAs PCSS during lock-on. The switch is submerged in an insulating liquid fluorocarbon (Fluorinert, 3M) and was clamped at the contacts (left -, right +) with cylindrical electrodes. These images are similar to those seen during electrical breakdown across the surface of a switch except for the absence of visible radiation. In contrast, a surface flashover spectrum has a strong component of blue to UV radiation. Except for occasional bright spots near the contacts, these images are completely invisible to the naked eye and totally blocked from the camera with an IR absorbing filter. The spectrum radiated from these lateral switches has not yet been measured. Notch filters with 50 nm transmission half-widths place the radiation at just below 850 nm. A spectrum that obtained was obtained from the ends of vertical switches was centered at 880 nm with a full width half max of 15 nm.[14] Since the nominal bandgap of GaAs, 1.41 eV, corresponds to 870 nm, we believe this radiation is produced by carrier recombination across the bandgap. Self-absorption by the GaAs would shift the spectrum to longer wavelengths as higher energies are more strongly absorbed. This shift may be useful in determining the depth of the radiation source.

Concentrated recombination might occur either at crystal defects where recombination is more likely or where the carrier concentration is high. Since these and other photographs show that the radiation pattern moves around in the switch from pulse to pulse, often showing more than one channel, we presume that this radiation pattern is evidence of current filamentation. Using a fast photodiode to detect the optical trigger and the photoluminescence, we have measured the time evolution of the luminescence and correlated it with the electrical signals from the switch. Our results show that whenever the switch is triggered into lock-on, strong photoluminescence is detected which is simultaneous with the switch current pulse. Figure 10 shows the signal from the photodiode. Both the photoluminescences pulse and the switch current pulse are 10 ns wide, although the photoluminescence pulse falls off more rapidly than the current.

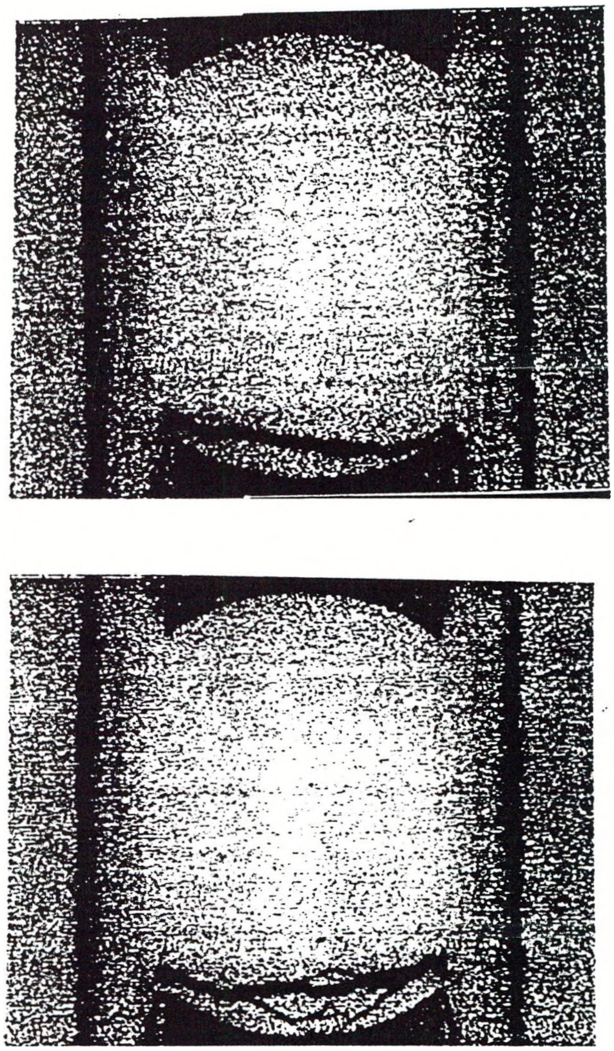

Figure 7. Infrared pictures of a 1-inch diameter PCSS during lock-on switching show evidence for current filamentation. (Negative prints are shown for clarity.)This switches were charged to 30-40 kV and triggered with 50-200 μJ of 532 nm radiation in 500 ps.

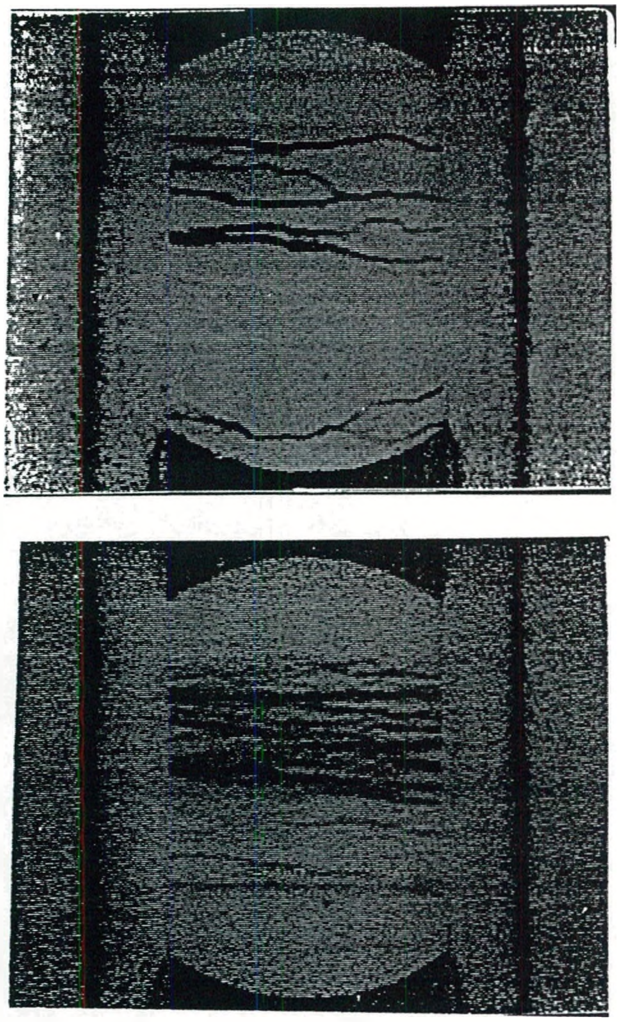

Figure 8. Infrared pictures (negative prints) as in the previous figure but with higher optical trigger energies, 0.5-2 mJ, reveal many filaments with a diffuse gray background (which may not reproduce well).

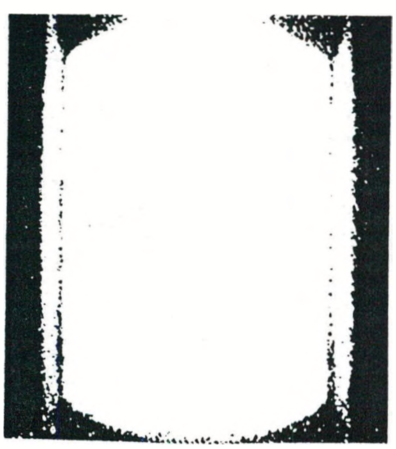

Figure 9. This infrared picture (positive print) shows a switch triggered with approximately 20 mJ of optical trigger energy. Relatively uniform recombination radiation is seen with little evidence for current filamentation.

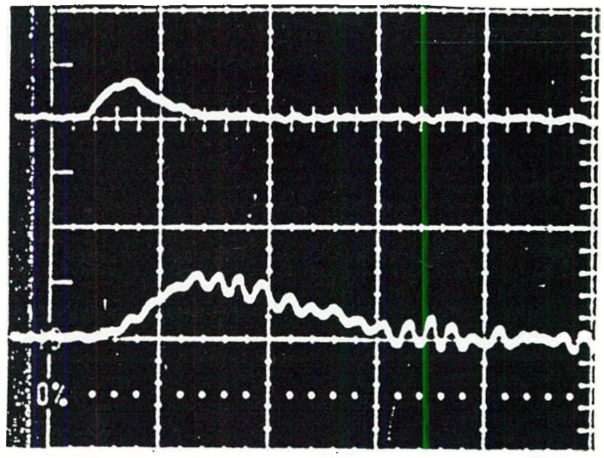

Figure 10. Light detected with a photo diode near the switch shows the optical trigger (top) and the photoluminescence (bottom) using a green filter to eliminate the 532 nm trigger. (Photodiode voltage vs. 5 ns / division)

All the pictures shown in figures 7 thru 9 were taken when the PCSS was charged to 30-40 kV, well above the 12 kV lock-on voltage. Figure 7 shows images obtained with weak optical triggers of 50-200 μJ. In these examples only one or two bright filaments are recorded. Figure 8 shows images obtained at somewhat higher optical trigger energy, (0.5-2 mJ). Many multiple filaments and a diffuse background are recorded here. Figure 9 shows the image obtained with intense optical triggering (~20 mJ). Radiation is relatively uniform indicating that intense triggering or linear switching shows no evidence for filamentaion even at voltages approximately three times the lock-on voltage.

Repetitive measurements with 2 mm long GaAs PCSS under Fluorinert reveal brighter visible regions near the contacts with the brightest region at the positive contact. Damage near the contacts appears to accumulate as successive filaments move to new positions along the contacts. Inspection of the switch shows damage to both the metallization and the semiconductor near the contact boundary. Continued tests have produced enough accumulated damage to actually fracture the wafer near the contact boundary. This gradual damage may simply be an indication of current pinching between the metallized contact and the semiconductor which might be reduced significantly with "deeper" contacts and smaller Schotky barriers.

The approximate size and location of the current filaments are difficult to estimate. The spectral shift and an edge view of a switch may indicate that the filaments are located relatively deep, below the surface of the switch. On the other hand, no filaments have been observed from the back (non-illuminated) side of the switch. This might indicate that they are not deep enough for the light to penetrate the 625 μm thick switch. The apparent diameter of the filaments from inspection of the photograph is less than 0.2 mm. Current during these tests has ranged from 100-300 A. This would imply average current densities 300-900 kA/cm^2 in the filaments. More accurate measurements of the size and location of the filaments are being pursued.

V. IMPLICATIONS

The data described in this paper have several implications for the theoretical explanation of lock-on and its practical application. First of all, the short delays to lock-on at high fields imply that most of the extra carriers generated in the lock-on mode must be created in the semiconductor, away from the contacts. If the switch had ideal injecting contacts, its size and shape give a space charge limited current flow of less than 1 A. The fact that several kiloamps of current can be produced within a few nanoseconds of the optical trigger implies that most of the extra carriers are not simply being injected from the contacts.

On the other hand, long delays to lock-on observed near the electrical and optical thresholds say something else about the initiation to lock-on. If the growth rate of lock-on is linear in the carrier density which is created initially by the optical trigger, then the switch resistance should decrease exponentially until the field across the switch drops to the lock-on field. However, the long delay and relatively fast rise time shown in figure 5 are not consistent with simple exponential growth in the carrier density.[16] A model which depends on a higher order or threshold in the carrier density is required by this data. At high fields, the delay and rise time decrease, but the rise time (600 ps) is apparently limited by something other than the optical trigger (200 ps). This effect might be a fundamental part of the explanation for lock-on or it might simply be caused by the inductance of the current filaments. If multiple filaments become more likely at higher fields, then a corresponding reduction in the rise time would be observed.

The mere existence of current filaments limits the scope of models to be explored. If the carrier generation during lock-on initiation is an effect caused by negative differential resistivity, then the shape of the I-V curve can be deduced from the fact that current filaments are formed.[16] Models giving S-shaped I-V curves imply filament formation. Charge domain formation is implied by models giving N-shaped I-V curves such as the explanation of the Gunn effect.

The damage caused near the contacts at the ends of the filaments is consistent with contact degradation reported previously. Improved contacts or methods to induce multiple filaments will surely decrease this damage and increase the device reliability. Several schemes to encourage the growth of multiple filaments have been suggested and are being explored. A model which explains the factors which control the size and location of the filaments should be very useful in this respect.

VI. CONCLUSION

This paper reports some of the switching properties of a high gain switching mode called lock-on in lateral GaAs PCSS. The rise time, delay, and minimum energy required to trigger high voltage switches has been measured and shown to be inversely related to the field across the switch up to 55 kV/cm (80 kV). Rise times as short as 600 ps, and trigger energies as small as 20 μJ were observed for these 1.5 cm long switches.

Photoluminescence from the switches during lock-on is strong evidence for current filamentation. This information limits the scope of theoretical models being suggested for lock-on and focuses our attention on schemes to induce multiple filaments for reliable high current devices.

VII. ACKNOWLEDGEMENTS

The authors would like to acknowledge several extremely valuable collaborations with scientists from other organizations. PCSS triggering with large solid state laser diode arrays was obtained in cooperation with Arye Rosen and Paul Stabile of David Sarnoff Research Center, Princeton, NJ.[11] Sub-nanosecond PCSS triggering was recorded in a series of experiments performed with Vic Carboni and Ian Smith of Pulse Sciences Inc., San Leandro, CA, and Robert Pixton and Mike Abdahlla of BDM International, Albuquerque, NM.[12] The first photoluminescence indicating current filamentation in lateral PCSS was recorded in collaboration with Aaron Falk, Jeff Adams, and Gail Bohnhoff-Hlavlacek of Boeing Aerospace and Electronics, Seattle, WA.[14] The photoluminescence measurements were also advanced with the generous loan of a short pulse laser diode and its associated electronics which was developed by several scientists at Power Spectra Inc., Fremont, CA.

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