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TRIGGERING GaAs LOCK-ON SWITCHES WITH LASER DIODE ARRAYS

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Abstract

Many of the applications that require the unique capabilities of Photoconductive Semiconductor Switches (PCSS) demand a compact package. We have been able to demonstrate that GaAs switches operated in the high gain mode called "lock-on" meet the required electrical switching parameters of several such applications using small switch sizes. The only light source that has enough power to trigger a PCSS and is compatible with a small package is a laser diode. This paper will describe the progress that leads to the triggering of high power PCSS switches with laser diodes. As of this writing, we have used an 850 W optical pulse from a laser diode array to trigger a 1.5 cm long switch that delivered 8.5 MW to a 38.3 Ω load. Using 166 W arrays we have triggered a 2.5 mm long switch delivering 1.2 MW with 600 ps risetimes at pulse repetition frequencies of 1 kHz. These 2.5 mm long switches were tested for pulse lifetime and survived 10^5 pulses at 1.0 MW levels. In single pulse operation we have switched up to 600 A with laser diode arrays. Our goal is to switch up to 5 kA in a single shot mode and up to 100 MW repetitively at up to 10 kHz. These goals are feasible since the switches can be used in parallel or in series.

Low light level triggering became possible after the discovery of a high electric field, high gain switching mode in GaAs (and later in InP). At electric fields below 3 kV/cm GaAs switches are activated by creation of, at most, only one conduction electron- valence hole pair per photon absorbed in the sample. This linear mode demands high laser power and, after the light is extinguished, the carriers live for only a few nanoseconds. At higher electric fields GaAs behaves as a light activated Zener diode. The laser light generates carriers as in the linear mode and the field induces gain such that the amount of light required to trigger the switch is reduced by a factor of up to 500. The gain continues until the field across the sample drops to a material dependent lock-on field. At this point the switch will carry as much current as, and for as long as, the circuit can maintain the lock-on field. The gain in the switch allows for the use of laser diodes.

Introduction: Lock-on GaAs

GaAs switches operate in the linear mode when they switch low fields [1]. At fields above 5.6 kV/cm, undoped GaAs (GaAs:EL2) is capable of switching in a non-linear mode [2]. Figure 1 shows how GaAs behaves in the linear mode and in the high field mode that we call lock-on. An aspect of lock-on that is crucial to many applications is the low laser power needed to trigger it. This trait allows the use of laser diode arrays that operate at high repetition rates.

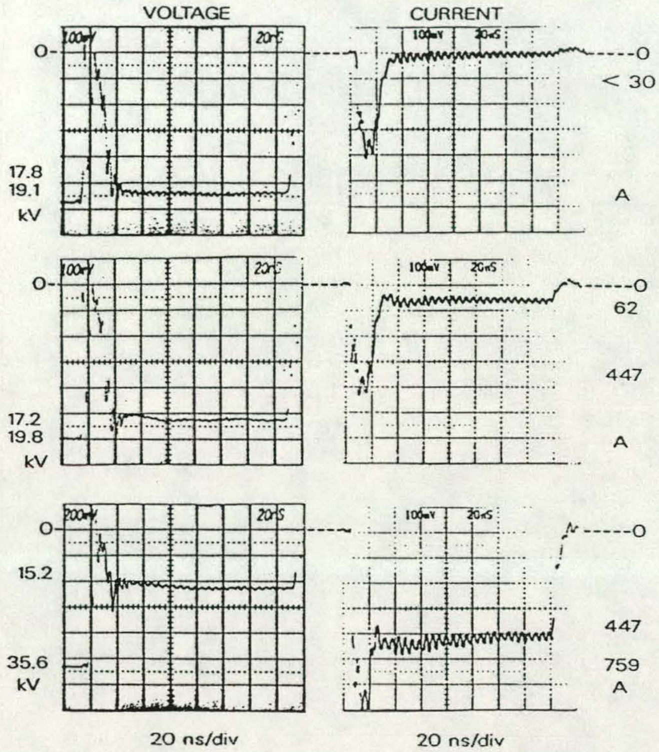

Figure 1. Waveforms of the voltage and current across a GaAs PCSS as a function of the applied voltage. For voltages above 19.1 kV GaAs acts as a closing switch.

The voltage and current waveforms shown in Fig. 1 are for a GaAs:EL2 switch 3.38 cm long. At 19.1 kV, the voltage across the switch drops to a very low value when the laser light (2.3 eV photon energy) hits the switch. The laser pulse is 10 ns wide during which electron and hole carriers are being created. After the laser pulse, the carriers recombine in nanoseconds, and the switch resistance and the switch voltage return to its original value. The current only lasts for 10 ns. When the voltage is increased, the waveforms look completely different. The voltage does not return to the original value, but to a fixed value that we call the lock-on voltage. The current continues for as long as the system can sustain it. Figure 2 shows the voltage waveforms that result from triggering a 2 mm long GaAs:EL2 switch into lock-on to illustrate that the triggered voltage is independent of charge voltage. Note that voltage is 1 kV which corresponds to 5 kV/cm. The lock-on field of this switch can be compared to that of Fig. 1 (4.5 kV/cm) to show that the lock-on voltage is given by a lock-on field times the switch length. For GaAs:EL2 switches we have varied the switch length from 0.1 cm to 3.38 cm and found lock-on fields that range from

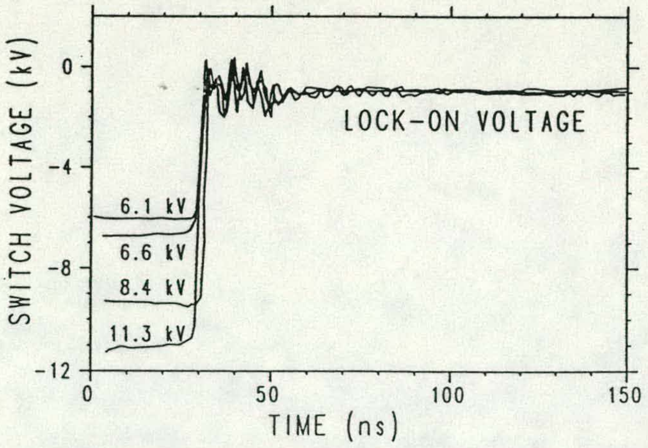

Figure 2. Waveforms of the voltage across a GaAs switch (0.2 cm long) for different charge voltages. The lock-on voltage is independent of charge voltage.

3.6 kV/cm to 4.5 kV/cm. Several other aspects influence the lock-on field; the most important of these is the type of GaAs material used. Chrome doped GaAs (GaAs:Cr) is the most common type of high resistivity GaAs. For GaAs:Cr we find a lock-on field of ~8- 9.5 kV/cm. We have been able to change the lock-on field of GaAs:Cr to 49 kV/cm by neutron bombardment and to 6.2 kV/cm by cooling to 77 K.

Lock-on switches can handle the high voltages and powers required by many applications, as illustrated in Fig. 3. Using a 3.4 cm long GaAs:EL2 PCSS we switched 112 kV to a lock-on voltage of 15.3 kV, with a current of 1.56 kA. The effective power into a matched load was 46 MW. While this voltage is high, the field is not the highest that we have switched: 57.1 kV/cm with a 1.5 cm long GaAs:Cr PCSS. Higher voltages can be switched by using the demonstrated PCSS in series. We found that three lock-on switches that individually can switch (at most) 11 kV can be used in series to switch 34 kV.

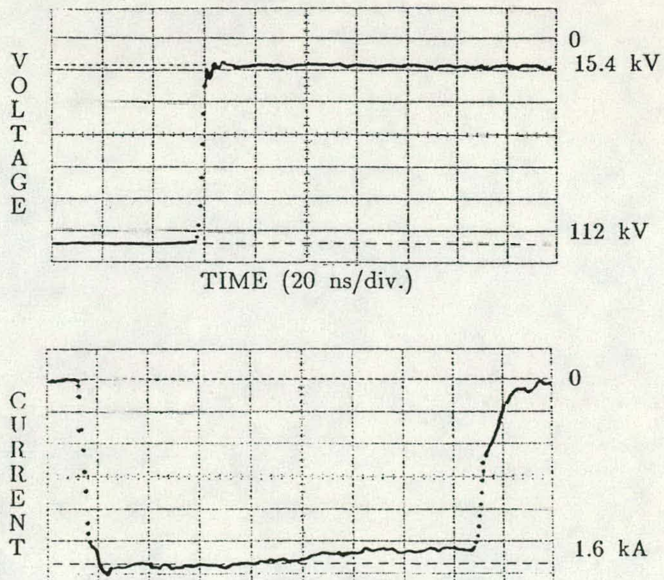

Figure 3. Voltage and current across a lock-on switch. This is the highest voltage switched, and for a matched load corresponds to 46 MW.

The second aspect of GaAs lock-on switches is that they can conduct high currents. Figure 4 shows the current obtained from switching an LRC circuit with lock-on GaAs [3]. At charge voltages below 2.0 kV the switch was below the lock-on threshold and the current was negligible. Above 2.0 kV the current rises linearly with a slope of 2.8 Ω. The impedance of the circuit is also 2.8 Ω. This shows that while the lock-on switch has a definite voltage drop across it, it will conduct as much current as the circuit allows. The current in the circuit is given by

$$I = (V_c - V_{lo}) / R_c, \quad (1)$$

where V_c is the charge voltage, V_{lo} is the lock-on voltage, and R_c is the circuit's impedance. Figure 5 shows that we used this property of lock-on to switch 4.0 kA with a circuit of 0.36 Ω impedance (V_c was 3.3 kV, and V_{lo} was 1.9 kV)[4]. The current was distributed over 2.1 cm. The current handling capability of a switch is determined by its width. Switches 0.25 cm long have carried up to 800 A (3200 A/cm).

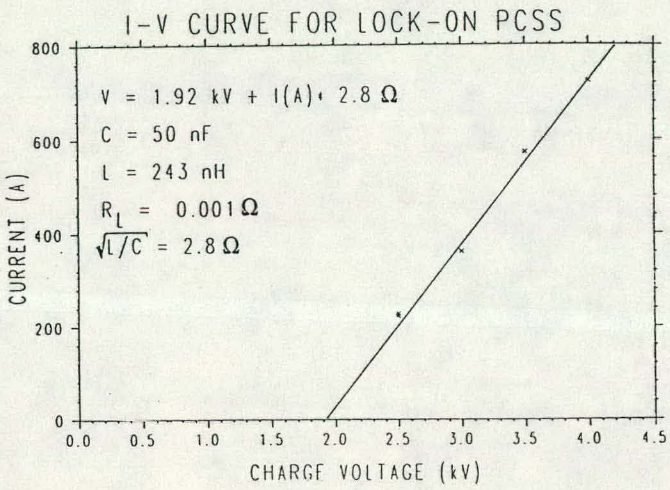

Figure 4. The current in an LRC circuit when switched with a lock-on GaAs switch. The line is a linear fit to the data and is given by the top equation. The parameters of the circuit are shown. Note the exact agreement between the inductance of the circuit and the "slope" of the curve.

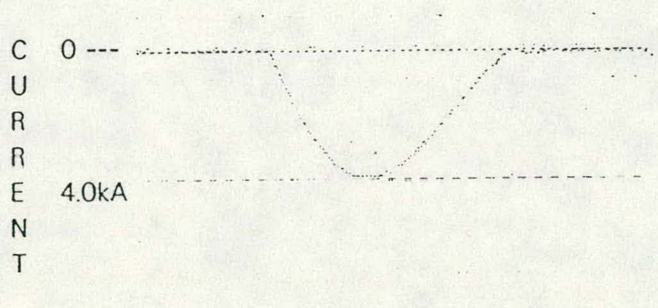

Figure 5. The current across a 2 mm long by 2.1 cm GaAs switch in a low impedance circuit (C= 200 nF, L≃ 26 nH, Rload= 0.0245 Ω) charged to 3.28 kV. The peak current is 4 kA, the highest that we have switched.

Lock-on Gain

Another aspect of lock-on is the ability to trigger with low light levels. Using 1.5 to 3.4 cm long switches, we observed that the amount of laser power required to trigger lock-on was 500 times lower than that for linear switching [2]. In particular, the lowest light levels that trigger lock-on barely drop the switch resistance of the same switch in the linear mode. This implies that there is a large gain (more carriers per photon) in lock-on. The gain explains the voltage drop across the switch since in any switch where there is a short carrier lifetime (as in GaAs) and a field dependent gain, these two mechanisms balance each other to create a voltage drop.

Triggering Lock-on Switches with Laser Diode Arrays

The gain allows the use of compact light sources such as laser diode arrays. We have triggered different types of GaAs into lock-on with laser diode arrays. We triggered a 1.5 cm long switch, that discharged a 50 Ω transmission line pulse charged to 55 kV, with a 850 W pulse from a laser diode array furnished by David Sarnoff Research Center [5, 6]. Figure 6 shows that the switch delivered 470 A to a 38.3 Ω load. The power was 8.5 MW. This result shows the ability of the switch to handle high voltages in a system of high impedance with laser diode arrays.

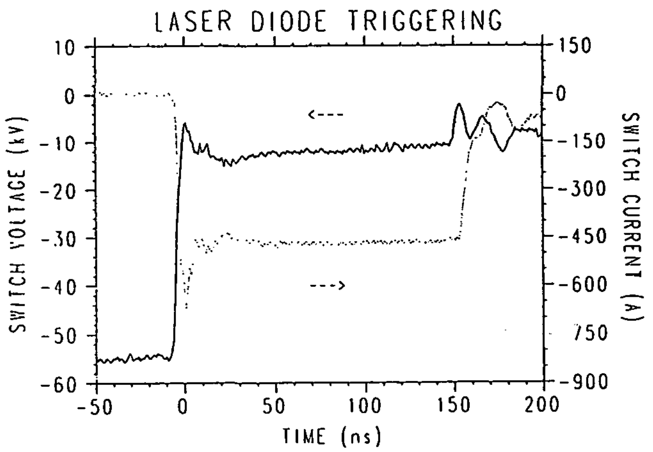

Figure 6. The voltage and current for a GaAs switch (1.5 cm long) triggered with a 850 W optical pulse from a laser diode array. The electrical power delivered to the 38.3 Ω load was 8.5 MW.

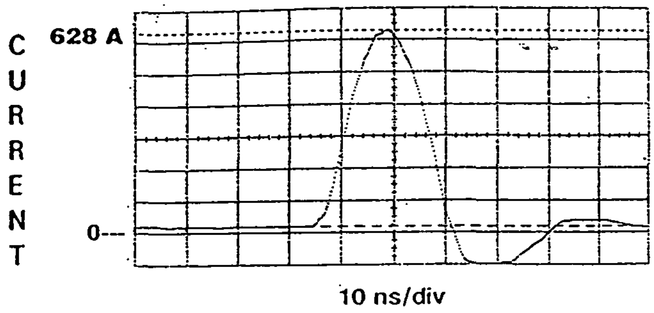

Figure 7. The current delivered by a 2.5 mm long by 2.5 mm wide switch when triggered by a laser diode array. The peak current was 628 A.

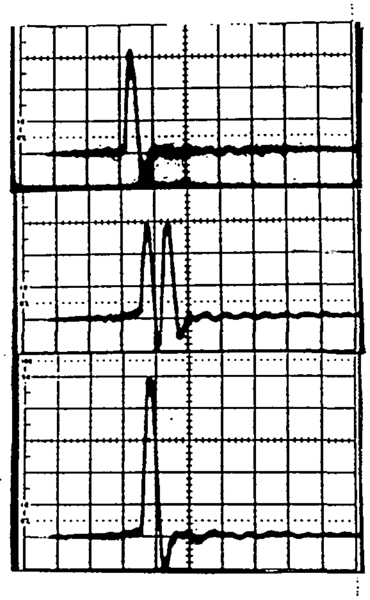

Figure 8. Current pulses from two switches and capacitors in parallel (at 20 ns/div). The top trace (a) shows the result of triggering one switch. The middle trace (b) shows the current obtained when one switch receives more illumination than the other one, and in the bottom trace (c) both switches are equally triggered. Note that the in trace c the peak current is double that of traces a and b.

Using a commercially available laser diode array (rated for 265 W) that produced pulses from 55 W to 166 W we have triggered small, 2.5 mm long switches. Figure 7 shows the current in an LC circuit when the switch is closed. The peak current reaches above 600 A as predicted by the lock-on circuit model described above. Although this switch was pulse charged, we have also switched dc voltages to reach 600 A. Higher currents can be obtained with laser diodes by using the switches as modules and placing them in parallel. Figure 8 shows preliminary results from our first test of using two switches and two capacitors in parallel. Trace 8a shows the current obtained by illuminating only one switch, for trace 8b the switches are not illuminated equally, and for trace 8c both switches are illuminated equally. It is not clear that the switches were triggered into lock-on but the current in the circuit doubled when both switches were fully illuminated.

The laser diode arrays can be triggered at high repetition rates. The 0.25 cm long samples have been run at up to 1 kHz at peak power of 1.0 MW. This is illustrated in Fig. 9. There we show the voltage on the primary of our pulse transformer (0 to 600 V) as it is discharged at a PRF of 1 kHz. In an expanded time scale (1 μs/div), the voltage across the switch is also shown. The issue of heat management is very relevant in the case of repetitive operation. The lock-on voltage results in uniform heat dissipation across the switch. For 100 MW, the switch would have a lock-on voltage of about 30 kV and conduct 820 A. At a duty cycle of 10^{-5}, the heat dissipation due to lock-on is only 246 W and can be removed by cooling.

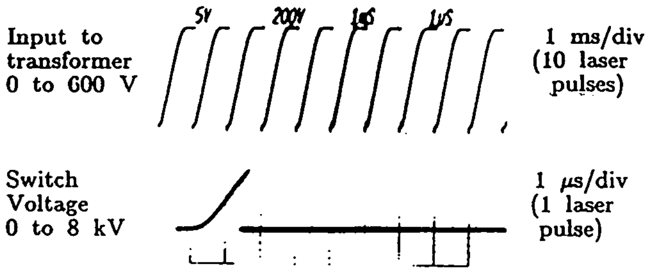

Figure 9. The charging waveform on the primary of the transformer at 1 ms/div showing switching at 1 kHz (top trace). The bottom trace shows the output of the transformer, which charges the switch, at 1 μs/div.

The ability to produce fast risetimes in the lock-on mode is being investigated presently. Figure 10 shows the current waveforms for the switch discussed in Fig. 6 to compare the linear and lock-on modes. At 30 kV, the field is below the lock-on threshold and the current pulse (left scale) waveform follows the optical pulse. The risetime of the pulse is 20 ns. At 55 kV, the switch is triggered in the lock-on mode and the risetime is faster than the laser pulse (~4 ns). This shows that the gain of lock-on can result in a faster risetime than that of the triggering laser pulse.

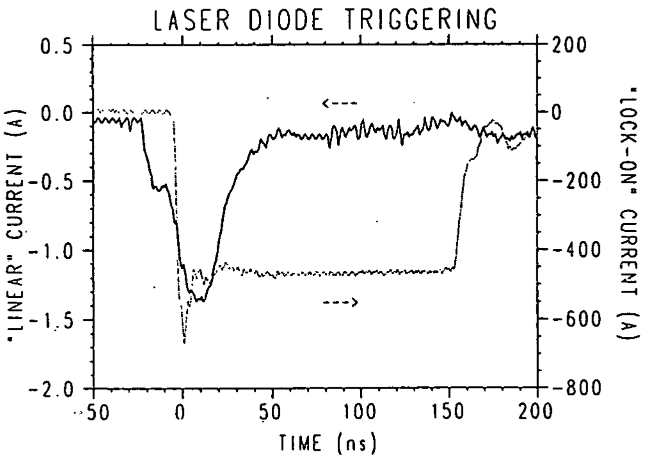

Figure 10. A comparison of the current waveforms of linear and lock-on switching. Both waveforms were produced by the same laser and switch but when the switch was charged to 30 kV the current pulse follows the laser intensity, and when charged to 55 kV GaAs went into lock-on. Note the differences in risetime, on time, and peak currents.

Figure 11 shows a current waveform produced by a GaAs lock-on switch triggered by the 265 W laser diode array [7]. The risetime of the current pulse is about 600 ps, roughly equal to the risetime of the laser pulse. The waveform shown in Fig. 11 represents 160 A with a 50 Ω load, reaching a peak power of 1.28 MW. The reproducibility of the waveform is good: <5% for the peak current, and <200 ps jitter. This type of switching was carried out at 1.0 MW level, at 1 kHz for 10^5 shots. The damage to the switch is at or near the metallized contact that serves as the cathode. The cathode and anode electrodes are made using a Ni-Au- Ge metallization scheme ubiquitous for GaAs [8]. For a 1 V barrier of 1 μm thickness, kiloamp currents can cause a local temperature rise that damages the small region. Repeated switching can cause thermal migration and reduce the effectiveness of the contact. We believe that using our present n-type contact for the anode together with a good p-type contact will improve the lifetime.

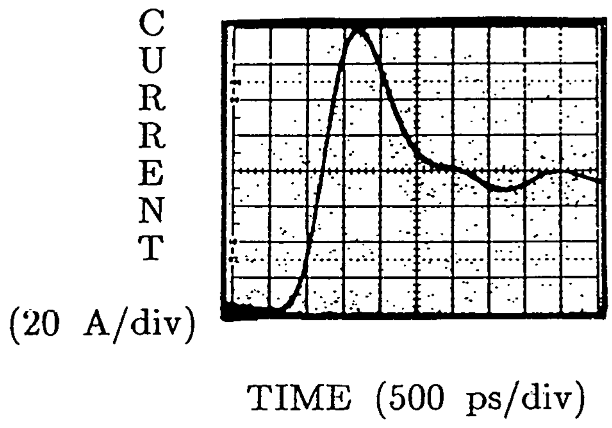

Figure 11. The current across a 50 Ω resistor switched by a 2.5 mm long switch that was triggered with a 33W laser diode array. The scale is 20 A and 500 ps per division. Thus the power is 1.28 MW, and the risetime is 600 ps.

Physics of Lock-on

We have studied the physics of lock-on extensively. Because of the low average (and local) lock-on fields that we measure, the mechanism probably is not avalanche. The linear dependance of the lock-on voltage on the switch length rules out current injection. We believe that the mechanism is related to negative differential resistivity (either voltage- or current- controlled) and that impact ionization from deep levels in the GaAs may also play a role.

Conclusions

We have shown that PCSS can be triggered with laser diode arrays. Accomplishments to date are: switch high powers (8.5 MW), switch high voltages (55 kV), switch high currents (600 A), trigger switches in parallel, fast risetimes (600 ps), and high pulse repetition rates (1 kHz). Issues under investigation are lifetime (presently at 10^5 pulses), risetime (<600 ps, circuit and diagnostic limited), and peak power capability.

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