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TRIGGERING GaAs LOCK-ON SWITCHES WITH LASER DIODE ARRAYS*

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Abstract

Laser diode arrays have been used to trigger GaAs Photoconducting Semiconductor Switches (PCSS) charged to voltages of up to 60 kV and conducting currents of 580 A. The driving forces behind the use of laser diode arrays are compactness, elimination of complicated optics, and the ability to run at high repetition rates. Laser diode arrays can trigger GaAs at high fields as the result of a new switching mode (lock-on) with very high carrier number gain. We have achieved switching of up to 10 MW in a 60 Ω system, with a pulse rise time of 500 ps. At 1.2 MW we have achieved repetition rates of 1 kHz with switch rise time of 500 ps for 10^5 shots. The laser diode array used for these experiments delivers a 166 W pulse. In a single shot mode we have switched 4 kA with a flash lamp pumped laser and 600 A with the 166 W array.

Introduction

Until recently, laser diode arrays were used to trigger lateral Photoconductive Semiconductor Switches (PCSS) that switched hundreds of volts at most. Voltages as high as 112 kV have been switched with GaAs but using a large flash lamp pumped laser. Two applications for laser diode triggered PCSS are impulse radar and firing sets. To assess the applicability to impulse radar we must switch 50 MW in a 50 Ω configuration (50 kV, 1.0 kA), with a rise time of 500 ps, a pulse repetition rate of 10 kHz, and a switch lifetime of 10^6 shots or more. For firing sets, our goal is to switch 5 kA in a single shot mode.

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 [1]. 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 carrier mulltiplllication (gain) such that the amount of light required to trigger the switch is reduced by a factor of up to 500 [2]. With gain, the

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current rises until the field across the switch drops to a material dependent lock-on field. At this point, the switch will carry as much current as the circuit will provide for as long as the circuit can maintain the lock-on field. This lock-on mode has been described in detail in other publications [3, 4]. The gain in the switch, when operated in the lock-on mode, allows for the use of laser diode arrays that operate at high repetition rates.

The characteristics of lock-on are: 1) The lock-on field is independent of charge voltage or switch length (the distance allong the field direction). 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 3.6 kV/cm to 4.5 kV/cm. 2) The lock-on field is dependent on many factors. One is the type of deep levels in the GaAs. For GaAs:Cr we find a lock-on field of ~8-9.5 kV/cm. Other factors are neutron damage and temperature. 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. 3) Lock-on switches can handle the high voltages and powers required by many applications. 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. Higher voltages can be switched by cascading PCSS. We found that three lock-on switches that individually can switch 11 kV can be cascaded to switch 34 kV. 4) The current through a lock-on switch is determined by the circuit and the lock-on field:

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

where V_c is the charge voltage, V_{lo} is the lock-on voltage, and R_c is the circuit's impedance. It is assumed that V_c is larger than V_{lo}. If not, the current is determined by linear photoconductivity. 5) Lock-on switches can conduct high currents. We have switched up to 4.0 kA with a 0.2 cm long by 2.1 cm wide (in the direction perpendicular to the field, across which the current is spread) switch. The circuit had 0.36 Ω impedance (V_c was 3.3 kV, and V_{lo} was 1.9 kV). The current handling capability of a switch is determined by its width. Switches 0.15 cm wide have carried up to 628 A (4187 A/cm). If we assume that this current is spread uniformly, and that it is due to electrons travelling at the saturation velocity of 2.0 x10^7 cm/s, the electron density would be 2.2 x10^{16}/cm^3. If the mechanism for lock-on depended on electrons coming from deep levels in the GaAs, the density of these deep levels would have to be larger than the above density. Since typical dopant and defect densities are of this order of magnitude, we would observe a saturation of the current for higher fields. This saturation has not been observed. 6) 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 comparable linear switching [2]. In particular, the lowest light levels that trigger lock-on barely drop the resistance of the same switch operating in the linear mode. This implies that there is a large gain (more carriers per photon) in lock-on. The gain is consistent with 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 in lock-on allows the use of very compact light sources such as laser diode arrays. We have triggered different types of GaAs into lock-on with laser diode arrays. We used a 850 W laser pulse to trigger a 1.5 cm long switch, that in turn discharged a 50 Ω transmission line that was pulse charged to 55 kV. The laser diode array was developed by the David Sarnoff Research Center [5, 6]. Figure 1 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 operate at high voltages with a laser diode array trigger.

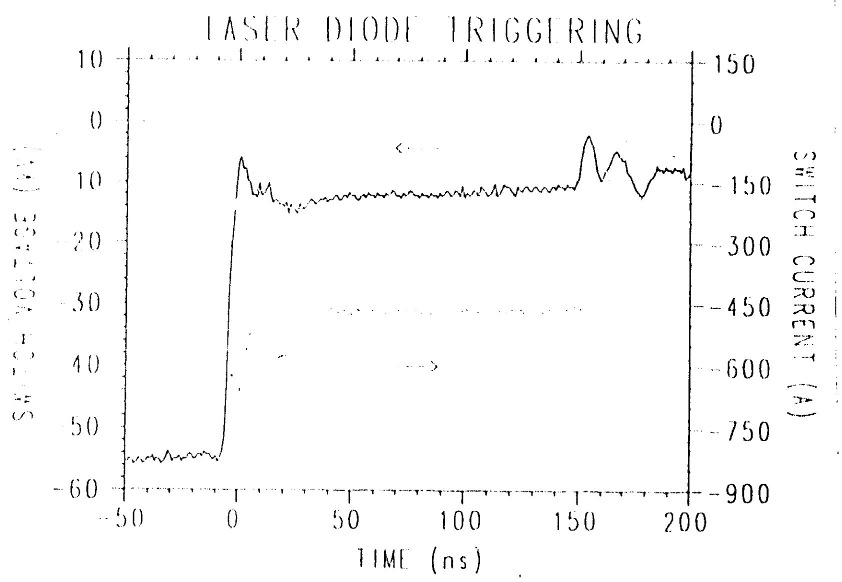

Figure 1. The voltage and current for a GaAs switch (1.5 cm long) triggered with a 850 W optical pulse from a laser diode array. The voltage across the switch drops from 55 kV to 12 kV upon triggering. The lock-on current is 470 A. The power delivered to the 38 Ω load was 8.5 MW.

Using a commercially available laser diode array (rated for 265 W) that produced pulses from 55 W to 166 W we have triggered many different types of switches with lengths that vary from 0.1 cm to 1.5 cm. The array is made from 40 individual GaAs diodes and emits at 904 nm (1.37 eV, slightly below the band gap of GaAs). The array is in a TO5 package about one centimeter in diameter and 0.7 cm long. The driver for the laser diode produces a 75 A pulse with a fast rise time at repetition rates as high as 1.0 kHz. We obtain a 50 μJ optical pulse with 600 ps rise time and 300 ns duration. The output of the laser diode array is shown in Figure 2. Since the switch is triggered into lock-on in less than a nanosecond, most of the optical energy is wasted. It is likely that a shorter light pulse with considerable less energy would trigger these switches.

The highest switch current and power that has been triggered with a laser diode array are 800 A and 10 MW. In that case, a three foot long antenna, whose impedance was roughly 60 Ω, was pulse charged to about 55 kV and discharged through a 1.5 cm long undoped GaAs lock-on switch with a lock-on voltage of about 6 kV. The laser used in this experiment was the small 166 W laser diode array. The current through the switch was measured with a 0.25 Ω current viewing resistor and is shown in Figure 3. The duration of the pulse is determined by the length of the antenna

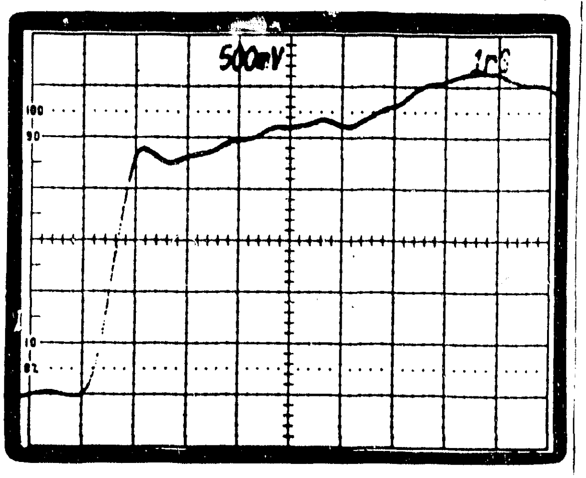

Figure 2. The optical pulse generated by our fast laser diode array. The time scale is 1 ns/div. The rise time is 600 ps.

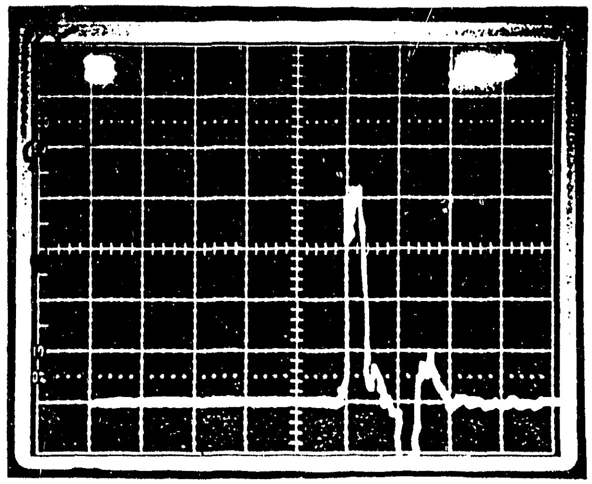

Figure 3. The current through a lock-on switch charged to 55 kV, triggered by a 166 W laser diode array. The scales are 200 A/div. and 20 ns/div. The peak current is 800 A. The power delivered to an ideal 60 Ω load would be 10 MW.

that acts as a three foot long transmission line. The peak current in the switch is 800 A. When the switch is triggered, a positive 49/2 kV voltage pulse moves through the switch away from the antenna. This pulse reaches the CVR which acts as a short at the end of the transmission line, thus doubling the current. The power delivered to an ideal 60 Ω load would be 10 MW. The measured current rise time is 600 ps but since the risetimes add in quadrature and the CVR has a bandwidth that corresponds to 300 ps, the switch rise time is 520 ps.

The highest current density that has been triggered with the 166 W laser diode array was 4.2 kA/cm (628 A). The GaAs switch was charged to 3.0 kV DC across 2.0 mm, and used to discharge a 2.1 nF capacitor through a load of 0.1 Ω and a stray inductance of about 30 nH. The lock-on field for the switch was about 4 kV/cm, satisfying equation 1. The current of 628 A was spread out across 1.5 mm, corresponding to a current density of 4.2 kA/cm, the highest that we have achieved.

The 0.25 cm long samples have been run at up to 1 kHz, at a peak power of 1.28 MW. Figure 4 shows the current pulse from such a switch. The waveform represents switching 160 A through a 50 Ω load for a peak power of 1.28 MW. The reproducibility of the waveform is good: <5% variation in 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 anode. Repeated switching ablates the metallized contact and some of the GaAs. This vaporization of material eventually leads to switch failure. The cathode and anode electrodes are made using a Ni- Au- Ge metallization scheme commonly used for GaAs [7]. This type of contact has a very low specific contact resistance (100 Ω μm^2), but is known to have a Schottky barrier height of, at most, 0.27 V to 0.35 V, with a transfer length of 0.2 μm to 0.6 μm. A current of only 500 A passing through a 0.25 cm wide

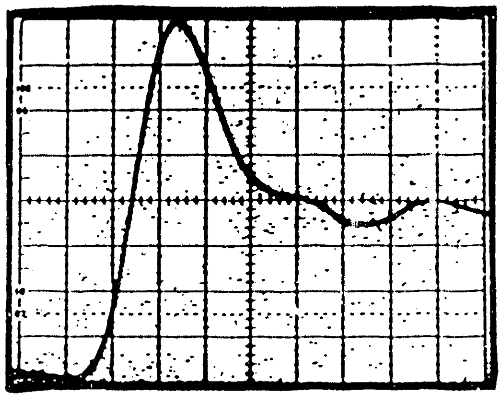

Figure 4. The current through a 50 Ω resistor switched by a 2.5 mm long switch that was triggered with a 166 W laser diode array. The scales are 20 A and 500 ps per division. Thus the power is 1.28 MW, and the rise time is 600 ps.

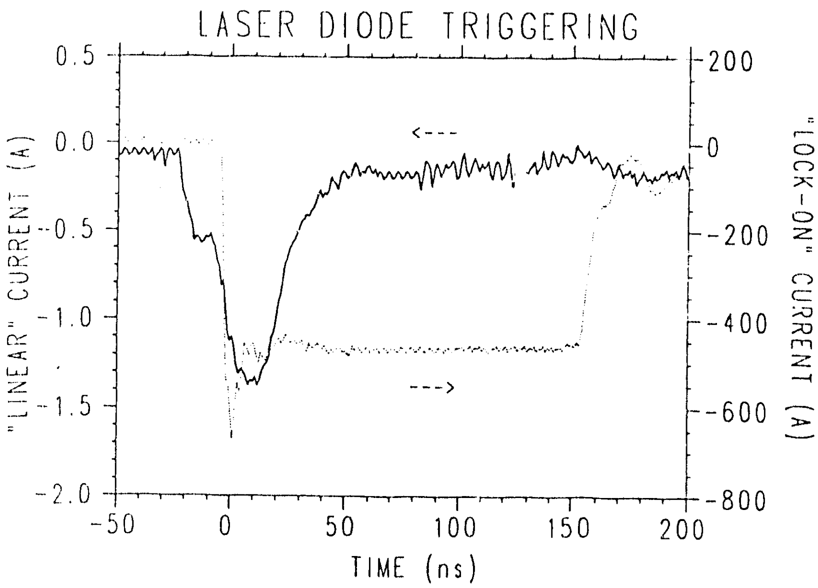

Figure 5. A comparison of the current waveforms of linear and lock-on switching. Both waveforms were produced by the same laser and switch but when the switch was charged to 30 kV the current pulse follows the laser intensity, and when charged to 55 kV GaAs went into lock-on. Note the differences in rise time, on time, and peak currents.

contact for 20 ns and such a voltage drop results in a temperature rise in the transfer region of 4000 C consistent with the observed damage. Further switching can cause thermal migration and reduce the effectiveness of the contact. Since this damage occurs mainly to the positive contact, we believe that using our present n-type contact for the cathode together with a good p-type contact at the anode will improve the lifetime. Another way to try to improve the lifetime is to use ion implantation to reduce the voltage drop and to increase the transfer length.

The ability to produce fast rise times in the lock-on mode is being investigated presently. Figure 5 shows the current waveforms for the switch discussed in Fig. 1 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 rise time of the pulse is 20 ns. At 55 kV, the switch is triggered in the lock-on mode and the rise time is faster than the laser pulse (~4 ns). This shows that the gain of lock-on can result in a faster rise time than that of the triggering laser pulse. Presently the best rise times that we have observed correspond to about 500 ps, as shown in figures 3 and 4.

Impulse Radar

There is considerable interest in the generation of subnanosecond rise time impulses to evaluate the feasibility of impulse radar. In this section we will use typical parameters to obtain the required switch parameters such as switch voltage, current, and length, laser input, power loss, and cooling necessary to assess the feasibility of impulse radar. Our calculations are for a switch that controls pulses of 50 MW peak power, with a rise time of 500 ps, a pulse duration of 1.0 ns, and a pulse repetition rate of 10 kHz. If we assume that the switches discharge a 50 Ω transmission line into a matched antenna, the switch must deliver 50 kV, and 1.0 kA. The highest field that we have switched for large samples is 42.7 kV/cm. Given a lock-on field of 4 kV/cm, the voltage delivered to a matched load is 0.5(42-4)L where L is the gap length. For a load voltage of 50 kV, L=2.6 cm. In practice we would use two 1.5 cm gap switches for a length of 3.0 cm. This requires two of the 166 W laser diode arrays. Note that the switch length implies a lock-on voltage drop of 12 kV. This voltage times the current times the duty cycle gives the power loss in the GaAs; 120 W. This loss would result in an unacceptable heating rate if it is not removed. Calculations indicate that cooling can be achieved by flowing the insulating dielectric liquid over the surface of the switch.

Physics of Lock-on

Several mechanisms for lock-on have been proposed. Because of the low average (and local) lock-on fields that we measure, the mechanism probably is not avalanche across the band gap. A simple model of current injection predicts that the lock-on field would vary linearly with the length of the switch and thus such a model would be inconsistent with the data [8]. A more complicated model that includes velocity saturation may reconcile this difference [9]. Regardless, any contact initiated mechanism has to contend with the very fast rise times and short delays observed. The rise times of 600 ps over distances of 1.5 cm would correspond to speeds of 2.5×10^9 cm/s that are even faster than the electron saturation velocity. A simple model where impact ionization from deep levels is the sole cause of lock-on is not sufficient since some of our switches have withstood high DC fields without going into lock-on. In particular, the undoped GaAs and the Cr doped GaAs switches (0.25 cm long by 0.25 cm wide) have withstood DC fields of 16 kV/cm for 60 minutes. This was done with the switches in the dark (current through the switches did not exceed 1.4 μA) and under room lights (with a current of 5.2 μA). A model of avalanche GaAs switches has been proposed by Falk [10] that seems to also explain some of the characteristics of lock-on. In this model the rate of growth of the free carrier number density (n) is given by:

$$dn/dt = -\alpha n + \beta n^2, \qquad (2)$$

where αn is the normal recombination term and β is an unknown, field dependent, carrier growth mechanism. This formula explains the requirement for a minimum light trigger level and the delays observed in lock-on. The physical reason for a term that produces carriers with the square of their density is typically a scattering mechanism. The scattering mechanism that is common to GaAs, InP, and most indirect band gap semiconductors is the excitation of electrons from the high mobility valley to the low mobility L valley in the conduction band. This gives rise to negative differential conductivity and to the Gunn effect. It is interesting to note that lock-on average fields are similar to the Gunn fields, although their temperature dependances are not the same [11]. Also, the transfer of electrons to the low mobility valley does not change the number of electrons and thus woulld not induce gain.

Conclusions

We have shown that PCSS can be triggered with laser diode arrays. Accomplishments to date are: high powers (10 MW), high voltages (60 kV), high currents (600 A), fast rise times (600 ps), and high pulse repetition rates (1 kHz). Issues under investigation are lifetime (presently at 10^5 pulses), rise time (<600 ps, circuit and diagnostic limited), and peak power capability. Our goal is to switch up to 5 kA in a single shot mode and up to 50 MW repetitively at up to 10 kHz.

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