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Physics and Applications of the Lock-on Effect*

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Abstract

The lock-on effect is a high gain, high field switching mechanism that has been observed in GaAs and InP. This switching mode is exciting because the amount of light required to trigger it is small when compared to triggering the same switch at low fields. For this reason we can use laser diode arrays to trigger high voltages, currents and power. This paper will describe the lock-on effect, and our recent experiments to understand the effect. We will show that impact ionization from deep levels cannot account for the observed current densities, delays, and rise times unless a second mechanism is invoked. We will also describe our applications for laser diode array triggered lock-on switches, the best results that illustrate our potential for the application, and the studies carried out to improve the lifetime and current carrying capability of the switches.

The Lock-on Effect

At electric fields below 3 kV/cm, GaAs switches are activated by the creation of 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, but the field induces carrier multiplication (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 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 characteristics of lock-on are many: 1) The lock-on field is independent of charge voltage or switch length (the distance along the field direction). For EL2 compensated GaAs (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 [4]. The lock-on effect has been observed in GaAs opto thyristors with lengths as small as 200 μm [5]. 2) The lock-on field is dependent on many factors. One is the type of deep levels in the GaAs. For Cr compensated GaAs (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 [6]. 3) The current through a lock-on switch is determined by the circuit and the lock-on field (independent of laser intensity). For example, in an RC circuit:

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

where V_c is the capacitor charge voltage, V_{lo} is the lock-on voltage, and R_c is the resistance. It is assumed that V_c is larger than V_{lo}. If not, the current is determined by linear photoconductivity. 4) 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. 5) The rise time of lock-on and the delay between trigger and lock-on have been studied as a function of switched field. Although long rise times and delays are observed when V_c is close to V_{lo}, the rise time can be as fast as 600 ps [7]. Typically, as the amount of light is increased, the delay to lock-on is reduced [7], but it is worthwhile to note that in a very restricted voltage range the opposite effect was observed (see below). 6) The lock-on effect was also observed in InP but has not been observed in Si even though fields as high as 82 kV/cm have been switched [8]. 7) The lock-on switches photoluminesce in the infrared. When this radiation is imaged, it is observed as filaments, providing direct evidence for current filamentation [7].

The Role of Impact Ionization and Deep Levels in Lock-on

One proposed mechanism for lock-on, that in particular explains the high gain in these switches, is impact ionization from deep levels, such as the ubiquitous EL2. The data shown below now suggest that the concentration of deep levels is insufficient to support the current densities observed in lock-on. The data also suggest that a simple one-step process is an insufficient explanation.

We have switched up to 4.2 kA with a lock-on switch that is 0.2 cm long by 3.0 cm wide (in the direction perpendicular to the field, across which the current is spread). The circuit consisted of a capacitor (C= 210 nF) in series with the switch, load (0.258 Ω), and current viewing resistor (0.005 Ω), and the stray inductance was about 25 nH. The capacitor was DC charged to 4.6 kV, and the switch triggered with a laser diode array that emitted 200 μJ of 830 nm radiation for 100 ns. The current waveform is shown in figure 1. The current handling capability of a switch is given by its width. Switches 0.15 cm wide have carried up to 628 A (4.2 kA/cm). If we assume that this current is spread uniformly and that it is due to electrons traveling at the saturation velocity of 2.0×10^7 cm/s, the electron density would be $2.2 \times 10^{16}/cm^3$. For filamentary current, the electron density would be larger. In some switches we have observed multiple filaments, but the overall effect is that the electron density in the filaments is above $2 \times 10^{16}/cm^3$. The switches that were used for these experiments were made from as-grown or GaAs:EL2. Typical EL2 concentrations do not exceed $2 \times 10^{16}/cm^3$. If the current in lock-on were only due to impact ionization from this EL2 level, the deep level concentration would barely support the current and could not support filaments.

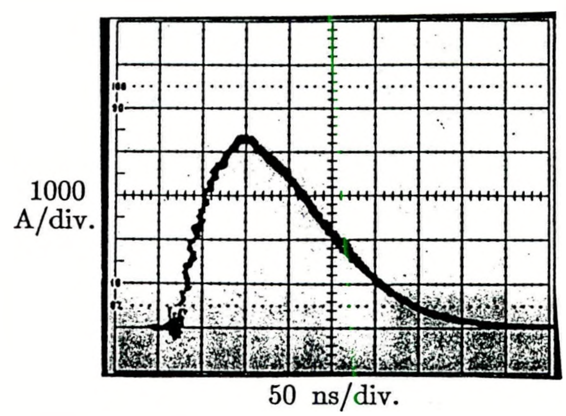

Figure 1. The current (at 1 kV/div.) across a 2 mm long by 3.0 cm wide GaAs:EL2 switch in a low impedance circuit (C= 210 nF, L= 25 nH, Rload= 0.263 Ω) charged to 4.6 kV. The switch was triggered with a 100 ns long pulse of over 200 μJ energy, from a laser diode array at 830 nm. The peak current is 4.2 kA, the highest that we have switched.

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To further investigate the importance of the EL2 level with respect to lock-on, tests were carried out in GaAs material that was treated to reduce the EL2 concentration. The switch was made from undoped (as-grown) GaAs that had been thermally processed by the inverted thermal compression (ITC) technique [9]. The key result of this processing is a controllable EL2 concentration ([EL2]). This switch had a relatively low [EL2] of $3 \times 10^{15}/cm^3$, compared to the untreated GaAs of $2.7 \times 10^{16}/cm^3$, as measured by high resolution optical absorption at the 1.039 eV zero-phonon line [10]. It is mainly the EL2 which compensates the residual shallow acceptors in this material, thus the low resistivity of 3×10^5 Ω-cm at at a temperature of 300 K [11]. To detect the presence of other traps, the GaAs was also characterized by thermally stimulated current (TSC) measurements. Only three peaks were observed in the TSC spectrum; and, although further work is in progress, they may be due to the EL6, HL9, HL10, and EL2 levels. An estimate of the trap concentrations indicates that they are all under $5 \times 10^{15}/cm^3$.

The ITC processed material was used to switch a 50 Ω, high voltage, 160 ns-long double transit time transmission line into a terminating load of ~38 Ω. The switch was triggered with 1064 nm radiation in order for it to penetrate the bulk of the material and cause uniform switching. The distance between the electrodes was 2 mm. Figure 2 shows the voltage across the switch. Note that the switched voltage is about 2.7 kV and that the laser initially causes linear photoconductivity, dropping the voltage to 1.7 kV. After a delay of about 56 ns, the switch undergoes lock-on. We first want to remark on the value of the lock-on field of this switch: 5.0 kV/cm. This value is typical of the lock-on field of GaAs switches that have EL2 concentrations that are at least an order of magnitude higher than in this ITC processed material. Thus, the ITC processed material shows the same lock-on field as non-processed material; the [EL2] does not couple strongly into the mechanics of lock-on.

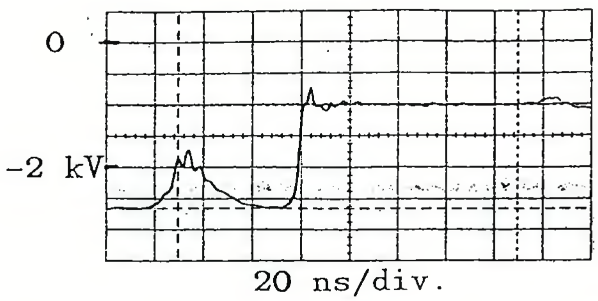

Figure 2. The voltage (0.5 kV/div) across an ITC-treated GaAs switch as function of time (20 ns/div). The switch was triggered by 59 μJ of 1060 nm light, that causes the first decrease in voltage (from 2.66 kV to 1.7 kV). The current at this point is 13 A. After a delay of about 56 ns, the switch locks-on. The lock-on voltage is 1.0 kV.

Figures 2 and 3 show the voltage waveform for the ITC-treated switch for two different light intensities (59 μJ and 14 μJ, respectively). In both cases, the charge voltage was about 2.66 kV, corresponding to a field of 13.3 kV/cm. Also, both levels of light illumination result in lock-on at a lock-on voltage of 1.0 kV (5.0 kV/cm). It is important to note that, when switched with 14 μJ, the delay to lock-on is about 20 ns while, with 59 μJ the delay is about 56 ns. When we used 280 μJ, lock-on was not observed (perhaps as a result of a very long delay to switching). Similar results were observed with a non-ITC-treated switch. In particular, when similar light intensities were used (as judged by the linear photoconductivity) roughly similar delays were observed. Also, the rise time of the lock-on (as observed in the current and voltage waveforms) is similar. Since the number of carriers generated by impact ionization is proportional to the initial number of carriers, we would expect that either the delay or the rise time of these two switches (ITC-treated and as-grown) to be different.

Because of the high current densities that have been observed during lock-on, and because of the similarity of the results obtained with ITC-treated and as-grown GaAs, we do not believe that impact ionization plays a large role in lock-on and cannot be the sole mechanism for lock-on.

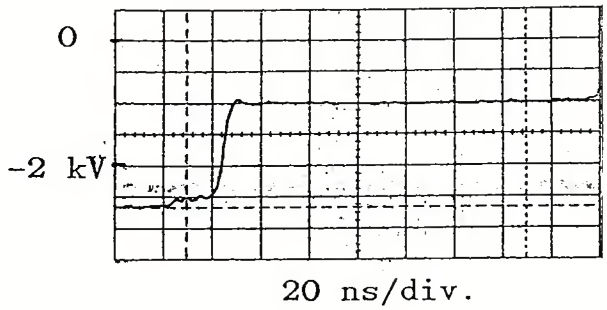

Figure 3. The voltage (0.5 kV/div) across an ITC-treated GaAs switch as function of time (20 ns/div). The switch was triggered by 14 μJ of 1060 nm light, that causes the first slight decrease in voltage (from 2.67 kV to 2.5 kV). The current at this point is 2.5 A. After a delay of about 20 ns, the switch locks-on. The lock-on voltage is 1.0 kV.

<u>Applications for Lock-on Switches, Contact Issues That Limit the Applications</u>

One of our applications for lock-on switches is in impulse radar. Using a flashlamp-pumped laser to trigger a 3.4 cm long GaAs:EL2 switch, 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. This illustrates the ability of a single lock-on switch to switch high voltages. Even higher voltages can be switched by cascading the switches. We found that three lock-on switches that individually can switch 11 kV can be cascaded to switch 34 kV.

For an impulse radar application, the switches must not only switch high voltages but they must be triggered at high repetition rates in the simplest possible way. For these two reasons, we have studied the ability of laser diode arrays to trigger the switch. We have used a laser diode array to trigger 42 MW in a 30 Ω system (1.2 kA) that, when broadcast by a small TEM antenna, produced near fields of 14 kV/m at a distance of one meter from the horn. Figure 4 shows the current waveform in the antenna, including ringing. The switch was made from undoped GaAs, with NiAuGe metallized contacts spaced by 1.5 cm. The switch was triggered with a small laser diode array that produced an optical pulse of 50 μJ with a rise time of 600 ps and a duration of 300 ns. The rise time of the switch current pulse was, at most, 600 ps. The repetition rate of the laser diode is 1 kHz. While we have run similar switches at that rate, their lifetime at 1 MW is 10^5 pulses. Our goal is to increase this lifetime by improving the contact metallization. The damage to the contacts and the GaAs has been studied with scanning electron microscopy (SEM).

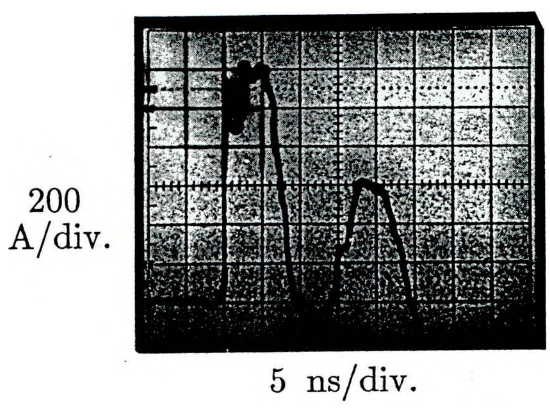

Figure 4. The current through a lock-on switch charged to 75 kV, triggered by a 166 W laser diode array. The scales are 200 A/div. and 5 ns/div. The peak current is 1200 A. The power delivered to an ideal 30 Ω load would be 40 MW.

The SEM study of the switches was carried out for five identical switches that were tested at varying conditions. The five switches were: 1) one that had not been switched or even soldered in the test circuit, 2) a soldered switch that was not triggered, 3) one subjected to 10K shots at 200 A per shot, 4) one subjected to 20K shots at 200 A, and 5) a switch subjected to 22K shots at 400 A. Figures 5 and 6 show views of switches 1 and 5. Note the erosion of the GaAs near the metallized contacts. The erosion results in a distance of only 2.1 mm between the damaged areas, compared to the original distance between the contacts of 2.5 mm. This shows that the damage not only extends into the metallization but also extends into the gap. Also note that one contact is more damaged than the other. This contact is the anode. We expect that a good positive contact will reduce the wear in our switches. Figure 7 shows the damage of switch 5, in the gap, at high magnification. Evidence of melting is visible here, but it represents not only the worst area of this switch but also one of the worst damaged switches that we have observed.

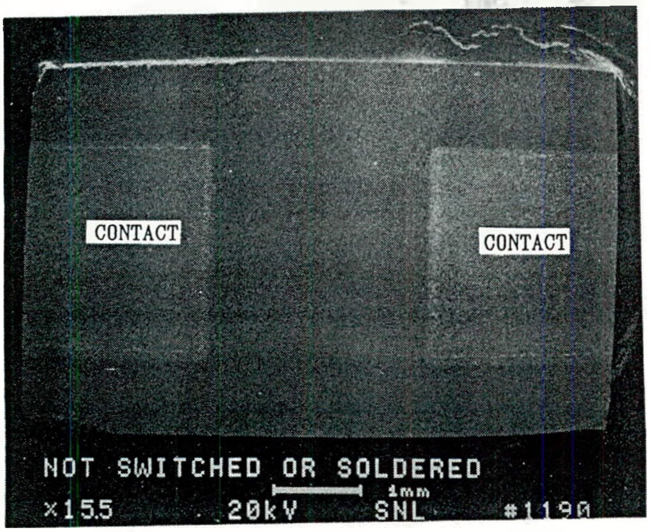

Figure 5. Low magnification SEM picture of our switch prior to its use. The distance between the metallized contacts is 2.5 mm.

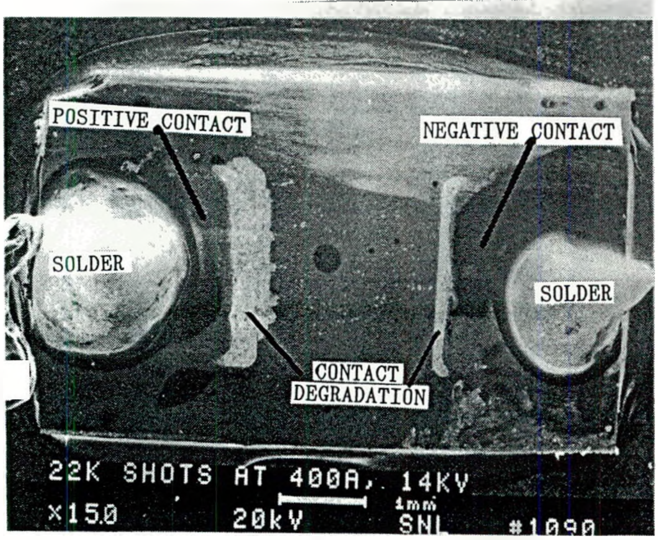

Figure 6. Low magnification SEM picture of a switch that was subjected to 22K shots at 400 A per shot until failure (switch 5). Note the erosion in the area near the contacts.

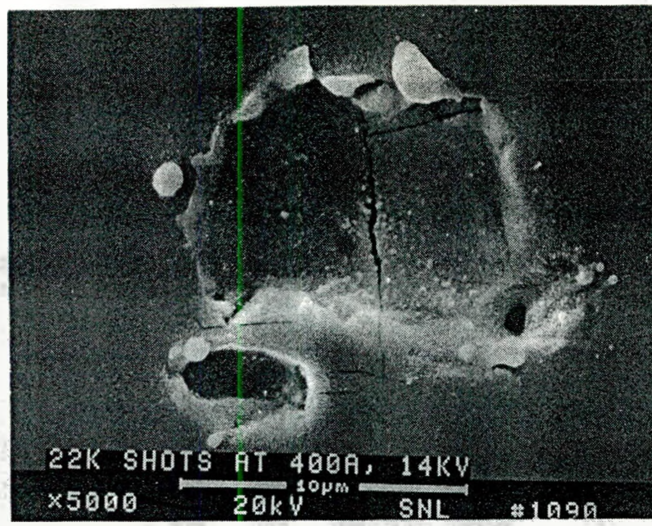

Figure 7. High magnification SEM picture of switch 5. Note that there is damage whose characteristic size is 10 μm and may exhibit melting.

To understand whether the filaments cause damage only on the surface that is illuminated by the light, and presumably carries the current, we cleaved switch 5. The new-exposed surfaces are perpendicular to the current flow, and we inspected the switch for damage that would correspond to a filament burrowing a "tunnel." That filament may cause damage that would appear on opposite sides of the cleave. The cleave causes considerable damage especially near the surfaces. Apart from cleave-related features, in the area near the edges of the new-exposed surfaces, there were no features or damage that could be caused by a deep filament. This appears to rule out damage from filaments in the bulk semiconductor. The problem of switch lifetime is being addressed presently: we are developing new AuZnAuNiAu (p-type) and AuBe (p-type) contacts for the anode.

Another application for switches that are laser diode triggered is in firing sets. We have triggered up to 4.2 kA with a laser diode array (see figure 1). The switch was made from undoped GaAs with NiAuGe metallized contacts spaced by 0.2 cm. To carry this large current, the contact metallization needs to be 3.0 cm in length. Although this laser diode array represents great savings in cost and size when compared to using a flashlamp pumped laser, the cost and size still exceed the constraints imposed by the program. Thus we need a more robust contact metallization so that the switches will carry higher current density, or we need a lower light trigger threshold.

Summary

We have presented in this paper our latest understanding of lock-on, the data that preclude the impact ionization mechanism from being the dominant mechanism for lock-on, our best results in laser diode triggered switches for high current (4.2 kA) and impulse radar (42 MW) applications, and our studies of switch degradation.

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