CLOSING PHOTOCONDUCTIVE SEMICONDUCTOR SWITCHES*

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Introduction

One of the most important limitation of Photoconductive Semiconductor Switches (PCSS) for pulsed power applications is the high laser powers required to activate the switches. In this paper, we discuss recent developments on two different aspects of GaAs PCSS that result in reductions in laser power by a factor of nearly 1000. The advantages of using GaAs over Si are many. First of all, the resistivity of GaAs can be orders of magnitude higher than that of the highest resistivity Si material, thus allowing GaAs switches to withstand dc voltages without thermal runaway. Secondly, GaAs has a higher carrier mobility than Si and, thus, is more efficient (per carrier). Finally, GaAs switches can have naturally fast (ns) opening times at room temperature and low fields, microsecond opening times at liquid nitrogen temperature of 77 K, or, on demand, closing and opening at high fields and room temperature by a mechanism called lock-on (see Ref. 1). By contrast, Si switches typically have opening times of milliseconds. The amount of laser light required to trigger GaAs for lock-on, or at 77 K, is about three orders of magnitude lower than at room temperature. In this paper we describe the study of lock-on in GaAs and InP, as well as switching of GaAs at 77 K. We shall show that when GaAs is switched at 77 K, the carrier lifetime is about three orders of magnitude longer than it is at room temperature. We shall explain the change in lifetime in terms of the change in electron capture cross section of the deep levels in GaAs (these are defect or impurity levels in the band gap). In the second section, we describe the lock-on effect, now seen in GaAs and InP, and at fields as high as 70 kV/cm. We show how lock-on can be tailored by changing the GaAs temperature or by neutron bombardment. In the third section, we discuss possible lock-on mechanisms.

GaAs at 77 K

When cooled to liquid nitrogen temperature (77 K), many of the properties of GaAs change dramatically. The low field mobility varies as much as $T^{-2.1}$, which implies an increase of a factor of 17 in the mobility, and a corresponding reduction of 17 in the laser power required to trigger a PCSS (at low fields) to a given resistance. In order to fully understand the effect of temperature on both low field and high field switching of GaAs, we tested the most common forms of semi-insulating GaAs: chromium-doped GaAs (GaAs:Cr) and EL2-compensated GaAs (GaAs:EL2). Both materials are semi-insulating, with resistivities above 10^7 Ω/cm, but they differ markedly in the way they are grown and the defects in the samples. The GaAs:Cr is grown by the horizontal Bridgeman technique and has Cr atoms as impurities. The GaAs:EL2 is grown by liquid-encapsulated Cochralski, are nominally undoped, and have native EL2 defects. The Cr impurities and EL2 defects have energy levels in the bandgap of GaAs, and affect its properties.

The switches consist of 7.5 mm long, 4.5 mm wide, and 0.6 mm thick pieces of GaAs with deposited metal contacts on the 0.75 mm x 0.45 mm face. The contacts are 2.5 mm squares separated by 2.5 mm. To metallize the wafer, they are first cleaned in a nine-step procedure, immediately transferred to an evaporator, where 50 Å-Ni, 750 Å-Ge, 750 Å-Au, 750 Å-Ni,and 2000 Å-Au are deposited without breaking vacuum. Next, the contacts are alloyed at 450 C for 30 s in a forming gas atmosphere. To perform experiments at low temperature (77 K), the samples are clamped to Cu-foils and placed inside a Styrofoam container. The circuit that we use to apply voltage across the sample consists of a critically damped LRC circuit (inductance of about 30 μH, resistance of 50 Ω, and capacitance of 45 nF). The capacitor discharges through a thyratron and the resulting pulse is shown in Fig. 1. The current through the switch was limited by a second 50 Ω resistor in series with the switch.

When GaAs is switched at room temperature and at low fields, the carriers created by the laser pulse recombine with a lifetime of approximately one nanosecond. Thus, the current through the switch lasts, at most, a few lifetimes after the laser pulse stops. Similarly, the voltage across the switch is reduced only during, and a few nanoseconds after, the laser pulse. The voltage waveform for switching GaAs:EL2 at room temperature is shown in Fig. 1. The laser is a frequency doubled Nd:YAG that results in a photon energy of 2.35 eV. The energy in the 10-ns wide pulse was <20 μJ (0.3 mJ/cm²). Figure 2 shows the results of switching GaAs at 77 K. Note that the voltage across the switch remains low for over a microsecond. This implies that the carriers have a much longer lifetime than at room temperature. The lifetime for the GaAs:EL2 was 2.4 μs at 77 K, compared to a few nanoseconds at room temperature. This increase of three orders of magnitude in the carrier lifetime is probably due to a reduction in the electron capture cross section of the EL2 level. It has been shown that the capture cross section decreases by three orders of magnitude in this temperature range.[2] A lifetime of microseconds is also obtained for GaAs:Cr in liquid nitrogen, and its capture cross section also shows a three order of magnitude decrease. To ascertain that our samples have these Cr and EL2 levels, the resistance of the samples as a function of temperature can be measured. The resistance varies exponentially with E/kT, where k is Boltzman's constant, T is the absolute temperature, and E is the activation energy for the deep level (energy to either remove electrons from the deep level or to excite electrons to

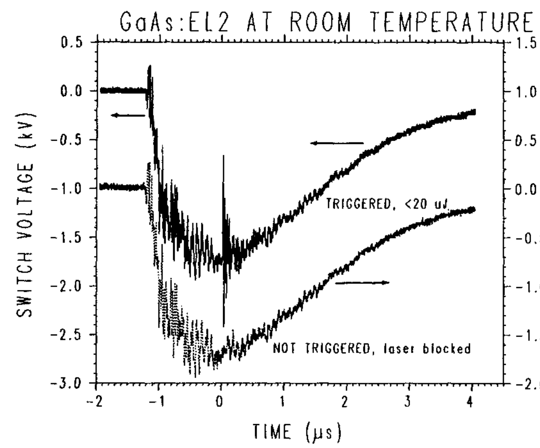

Figure 1. The voltage across a GaAs:EL2 switch at room temperature when triggered by a laser pulse of 10 ns width and total energy of <20 μJ, as compared with the voltage pulse when the laser does not activate the switch. Note that the voltage drops but recovers due to the short lifetime of the carriers at room temperature and low fields.

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14. ABSTRACT

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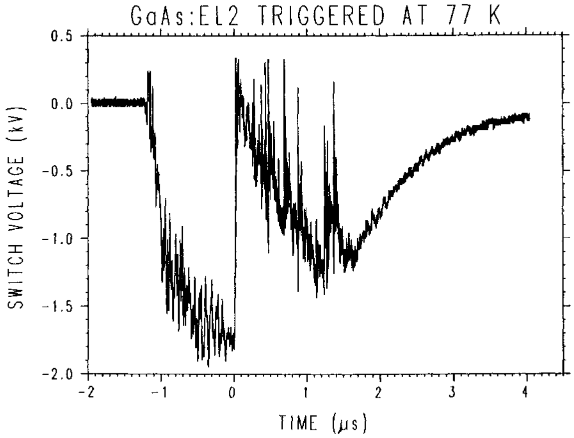

Figure 2. The voltage across the same switch as in Fig. 12 when triggered at 77 K temperature. Note that the switch does not recover as fast as when it is at room temperature.

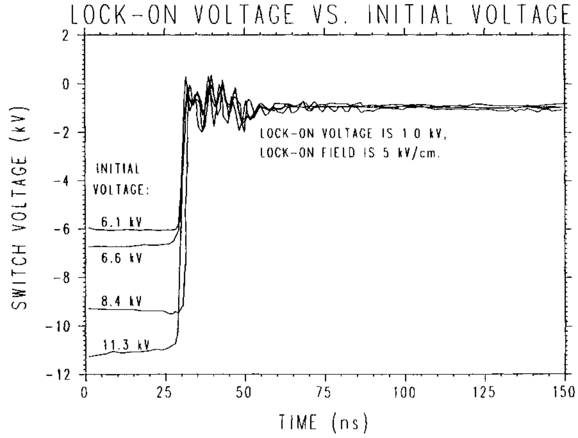

Figure 3. Switching GaAs at high fields. Note that the voltage across the switch does not recover as in Fig. 2. The voltage locks-on to a particular value that is independent of the charge (initial) voltage).

it). Values of 0.63 eV and 0.64 eV are obtained for the deep levels in our Cr: and and EL2: GaAs, respectively. The Cr level in GaAs is known to be an acceptor of electrons and is 0.63 eV below the conduction band.

We triggered GaAs:EL2 at room temperature and 77 K with nearly identical laser pulses. The minimum resistance of the switch is only a factor of about 1.6 lower at 77 K than at room temperature. Assuming that the carrier densities reached with the laser were identical, this implies that the mobility of the carriers at 77 K is about the same as that at room temperature. This change is very small when compared to the change in the low field mobility. The high field (above 3 kV/cm) properties of GaAs are indeed very different from those at low fields.

The large change in lifetime, coupled with the change in mobility as GaAs is cooled from room temperature at 77 K, combine to change GaAs from a closing and opening switch into a closing switch, and reduces the amount of laser power required to trigger GaAs switches by three orders of magnitude at 77 K.

Lock-On GaAs

The previous section emphasized the changes in GaAs as it is cooled to liquid nitrogen and is switched at low fields. This section will emphasize similar size but unrelated gains that occur at high fields. Two years ago we reported[3] that, when switched at high fields, GaAs exhibits a new switching mechanism called lock-on. Most of the lock-on tests were carried out using a circuit that consists of an LRC section that is critically damped and charges an 80-ns long (single transit), 50-Ω transmission line that discharges through the switch once it is laser triggered.[3] As discussed above and illustrated in Fig. 1, the carriers in GaAs have a recombination lifetime of nanoseconds at low fields and room temperature. If the same PCSS is switched at higher fields, the voltage waveforms are extremely different. Figure 3 shows the voltage waveforms for this switch when triggered at increasing fields. This switch eventually reached 70 kV/cm, the highest field we have switched with GaAs. Note that in all of the waveforms, the laser pulse closes the switch, but as the voltage recovers to a critical value, it stops rising. The switch locks-on to a specific voltage that is independent of charge voltage or current, and is linearly dependent on the distance across which the voltage is dropped (the "gap" spacing). For a given type of sample, the lock-on voltage is equal to a lock-on field times the gap spacing. The first property of lock-on is that it is a field effect: For a given type of sample, the charge field must be above a given value, and the voltage dropped across the sample is fixed by a lock-on field and the gap spacing.

The second trait of lock-on is that it can be triggered with very little laser energy. Thus, there must be a large gain in carrier population over and above the carrier population created by the laser. The total energy required to trigger lock-on is about three orders of magnitude smaller than necessary for low field switching. We believe that the gain is the result of electron multiplication, consistent with the fact that lock-on currents have persisted for over microseconds after the laser pulse is off. A third property of lock-on is that, while the switch retains the lock-on voltage, the lock-on current is equal to the difference between the charge voltage and the lock-on voltage divided by the circuit's impedance, as if the switch had no resistance. This statement has been tested in the 50-Ω system described above, as well as in 2.8-Ω and 0.7-Ω impedance circuits. The switch has not added any resistance to limit the current. Figure 4 shows the current in the 2.8-Ω circuit as a function of charge voltage. A linear least-squares squares fit of the data shows an intercept of 1.9 kV, agreeing with the measured lock-on voltage and a slope of 2.8 Ω which is equal to the $\sqrt{L/C}$ impedance of the circuit. Thus, the switch during lock-on behaves as a perfect voltage source across which a fixed voltage is dropped, but exhibits no measurable resistance (less than 0.2 Ω).

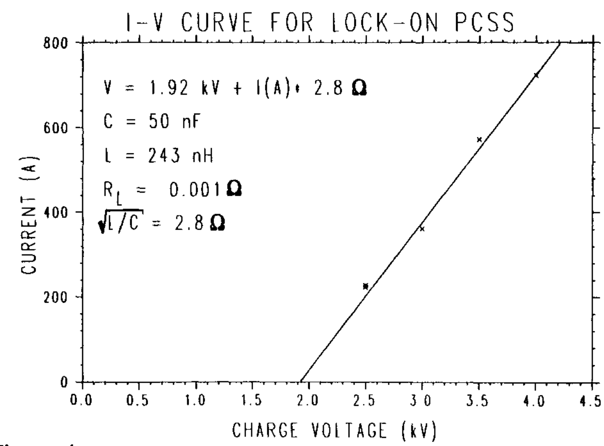

Figure 4. The current across a GaAs switch in an LC circuit with impedance of 2.8 Ω. The intercept on the voltage scale is the lock-on voltage and the slope is equal to the impedance of the LC circuit. This illustrates that the lock-on switch behaves as a very low impedance voltage source.

Recently, we tested the dependance of the lock-on field on the amount of neutron bombardment of the GaAs. This treatment increases damage (creating, among others, EL2 defects), decreases the mobility, and decreases the electron lifetime. GaAs:Cr switches were exposed to different neutron fluences of up to 5 X $10^{15}/cm^2$. While the lock-on field for the unbombarded samples was about 8 kV/cm, the neutron bombardment increased the lock-on field. For a field of 62.4 kV/cm, a neutron damaged (5 x $10^{15}/cm^2$) switch closes (only to 56 Ω) and opens to the original voltage. For an initial field of 67.5 kV/cm, triggering results in lock-on at about 49 kV/cm.

We have also tested how cooling affects lock-on. Cr: and EL2: GaAs are switched, at 77 K, in the circuit escribed in the preceding section. Figure 5 shows the results of switching Gaas:cr:cr at room temperature and 77 K. The lock-on field is reduced from about 8 kV/cm to 6.2 kV/cm upon cooling. For GaAs:EL2, the reduction in temperature does not appreciably reduce the lock-on field from its room temperature value of 4 kV/cm.

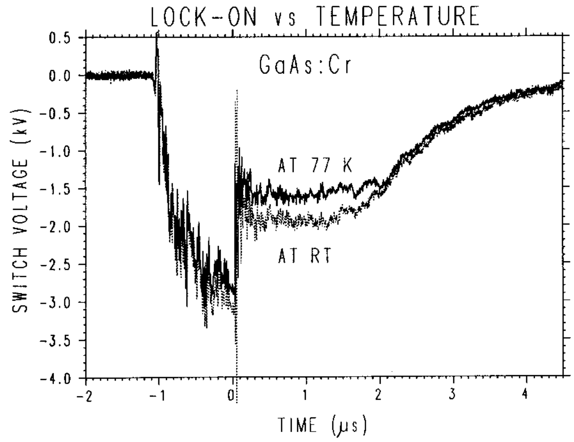

Figure 5. Switching of GaAs:Cr at high fields, at room temperature and 77 K. Note that the lock-on field at room temperature is higher than at 77 K.

In summary, there are four major properties associated with lock-on. First, it is a field effect. The field has to be above a value that depends on the sample characteristics and, once triggered, the voltage dropped across the switch is linearly proportional to the length across which the voltage is dropped. Second, there is a large gain, i.e., only a small laser energy is required for triggering and the lock-on persists after the laser pulse is gone, provided the circuit can provide the current. Not only does it require a small-power laser pulse to trigger, lock-on persists for as long as the circuit can supply current. If the field across the switch is forced to drop below the lock-on voltage, the switch will open. Third, it requires light triggering while the field is present (we have only seen lock-on with both light triggering and the high field). Fourth, the lock-on field is dependent on neutron bombardment fluence, temperature, and Cr concentration.

In order to test the universality of lock-on, we continue to test other materials. Lock-on is not observed in Si or in Au:Si, even though the latter has a carrier lifetime of less than 20 ns and is switched at high fields. Si is an indirect band gap material and does not exhibit some of the high field effects (such as negative differential resistivity) of direct bandgap materials like GaAs and InP. Switching Fe:InP at 24.1 kV/cm does not result in lock-on. Switching Fe:InP at 28.2 KV/cm results in lock-on at 14.4 KV/cm.

Mechanism of Lock-On

Switches with higher lock-on fields are needed for applications that require fast opening times, whereas low lock-on fields are needed to reduce the I x V (lock-on) power loss in the switch. In order to tailor the lock-on fields, we need to understand the fundamental mechanism responsible for lock-on. Although other workers have reported phenomena similar to lock-on,[4] we are not aware of any mechanism that fully explains lock-on. At present, we are attempting to determine the static current-voltage characteristics of our samples to determine if lock-on follows from static negative differential conductivity or transient photoconductivity. It is well known that double carrier injection can produce effects similar to lock-on,[5] however, this model predicts a lock-on field that is strongly temperature dependant and also scales with sample length. Both of these facts are in contradiction with our data.

We are investigating multiple Gunn domains[1] or impact ionization of deep levels as possible mechanisms. Impact ionization implies that high velocity (or energy) electrons in the conduction band collide (impact) with electrons in defect or impurity states and promote them to the conduction band (ionization). In the dark, impact ionization is slow due to the low free carrier densities, but its rate is catalyzed by photogenerated carriers. This mechanism predicts a unique lock-on field that is independent of sample length and whose magnitude is also consistent with the data. Impact ionization also predicts gain in agreement with the experiments. Finally, impact ionization predicts that a switch in the dark will exhibit lock-on seconds after the field is turned on. However, this prediction is in disagreement with one experiment in which GaAs:Cr withstood a field of 16.8 kV/cm for about 30 minutes.

Conclusions

In this paper have demonstrated a large temperature dependance of the characteristics of GaAs PCSS. The most dramatic effect is a factor of 1000 increase in the lifetime of the carriers as the sample is cooled from room temperature to 77 K. The explanation for this effect is likely the factor of 1000 change in the electron capture cross section of the deep levels in our samples. In addition, we have investigated the effects of neutron bombardment and temperature on lock-on, both of which are consistent with an impact ionization model for lock-on.

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