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13. ABSTRACT (Maximum 200 words)

We have successfully produced an optically triggered thyristor based in GaAs, developed a model for breakdown, and are developing 2 related devices, including a GaAs based static inductor thyristor. We are getting at the basic limitations of GaAs for these applications, and are developing models for the physical processes that will determine device limitations. The previously supported gas phase work - resulting in the back-lighted thyatron (BLT) - has actually resulted in a very changed view of how switching can be accomplished, and this is impacting the design of important machines. The BLT is being studied internationally: in Japan for laser fusion and laser isotope separation. ITT has built a BLT that has switched 30 kA at 60 kV in testing at NSWC Dahlgren and the device is being commercialized by another American company. Versions of the switch are now being tested for excimer laser and other applications. Basically, the switch, which arose from pulse power physics studies at USC, can switch more current faster (higher di/dt), with less housekeeping, and with other advantageous properties. There are a large number of other new applications, include kinetic energy weapons, pulsed microwave sources and R.F. accelerators.

14. SUBJECT TERMS

Optically triggered thyristor, GaAs, GaAs based static inductor thyristor, Back-lighted thyatron, Solid state switches

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Lock-on effect in pulsed power semiconductor switches

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ABSTRACT

Certain high voltage pulsed power switches based on semi-insulating GaAs or InP exhibit a "lock-on" effect. In this paper, this effect is argued to be fundamentally a transferred-electron effect, and its experimentally observed characteristics are explained. The lock-on effect causes high forward drop and high power dissipation for certain pulsed power switches based on GaAs and various other direct gap materials.

Pulsed power devices based on semi-insulating (SI) GaAs or InP are observed to exhibit a unique property, commonly called the "lock-on" effect. This effect is most conspicuous in bulk switches comprised of undoped or Cr-doped GaAs and Fe-doped InP,¹⁻⁵ but is also observed in junction devices with thick SI GaAs base layers.⁶ Figure 1 shows the results of a typical experiment in which an opto-thyristor with a 200- μm SI GaAs:Cr base layer is optically triggered. In the ON-state, the device locks on or latches on to a forward drop voltage of ~ 100 V or field of ~ 5 kV/cm. In this paper, a model that can explain all the experimentally observed characteristics of the lock-on effect is presented, but more importantly, implications of this model for materials under consideration for pulsed power applications are discussed.

Any model of the lock-on effect must qualitatively and quantitatively explain the experimentally observed characteristics of this effect, which include the following:¹⁻⁶

- It is observed in devices fabricated with SI GaAs or InP but usually not with Si,^{3,4} and is usually triggered into the lock-on state with an optical or electron beam.¹⁻⁶
- The current vs. voltage (I-V) characteristic of a lock-on device is of the current-controlled negative differential resistivity (CCNDR) type or the S-type (schematically shown in the bottom inset of Fig. 1), and has two distinct features: a low-current, OFF-state branch, characterized by a threshold voltage (V_{th}); and a current-independent, ON-state branch, characterized by a lock-on voltage (V_{lo}).
- The lock-on electric field for a given material is independent of the lock-on state current and the pre-trigger bias field, and is substantially larger for InP than for GaAs. Typical fields are ~ 5 kV/cm for GaAs:Cr in opto-thyristors,⁶ ~ 8.5 kV/cm for GaAs:Cr photoconductive switches,⁴ ~ 3.6 kV/cm for undoped GaAs,⁴ ~ 4.8 kV/cm for GaAs:Cu:Si,² and 14.4 kV/cm for InP:Fe.³

- With higher defect density, the lock-on voltage is larger. A neutron bombarded GaAs sample showed a lock-on field of ~ 49 kV/cm with minimum pre-trigger bias of 67.5 kV/cm.³
- At lower temperature, the lock-on field is smaller. For a GaAs:Cr sample, the lock-on field decreased from ~ 8 kV/cm at room temperature to ~ 6.2 kV/cm at 77 K.³
- The pre-trigger bias field must be larger than a certain minimum field that is greater than the lock-on field. For InP:Fe, ~ 28.2 kV/cm were required before locking on to 14.4 kV/cm;³ for GaAs:Cu:Si, ~ 10 kV/cm were needed before locking on to 4.8 kV/cm.²

Double injection has been proposed as a possible mechanism for lock-on,⁷ and internal reabsorption of recombination radiation was used to explain the CCNDR observed in Si GaAs:Cr p-i-n diodes.⁸ These models may be able to reproduce qualitatively the lock-on behavior, but cannot account for all the lock-on characteristics quantitatively. We argue here that the lock-on effect is fundamentally related to the transferred-electron (TE) effect⁹ and instabilities associated with it. This explanation is supported by the observation of the lock-on effect in GaAs and InP (which have bandstructures that favor the TE effect) but not in Si (which has a bandstructure that does not).

The presence of a larger concentration of native defects in GaAs and InP than is found in Si can also strongly affect the I-V characteristics of these materials. Such defect related effects are accounted for in our model, which includes the trapping-scattering effects of deep levels. However, we show elsewhere¹⁰ that the same type of material bandstructure which is responsible for the TE effect⁹ is also necessary for lock-on to occur. In particular, in our model, a conduction bandstructure like those of GaAs and InP with a lower-lying, small effective mass (high mobility) direct-gap valley and a higher-lying, large effective mass (low mobility) indirect-gap valley is required.

We also note, in passing, that I-V characteristics of the CCNDR type have also been observed in Si p-i-n structures.¹¹ However, the mechanisms responsible for the behavior are very different than the bandstructure related mechanism responsible for the TE effect. Thus, within our model, they are unrelated to the lock-on effect also.

An explanation of lock-on based on the TE effect has previously been proposed by others,^{4,12,13} but their analyses were either incomplete or inconclusive. In addition to the TE effect, the present model includes impact ionization due to high field charge domains, trapping-scattering effects due to deep levels, and filament formation. While all of these effects are found to be essential in determining the details of the lock-on characteristics, such as, for example, the threshold field for lock-on, the lock-on effect itself is fundamentally related to the same conduction bandstructure characteristics responsible for the TE effect. We distinguish between threshold effect, wherein collisional processes resulting from the presence of scattering centers can result in lock-on and the physical mechanism responsible for lock-on which is a bandstructure effect.

The TE effect leads to a negative-differential mobility (NDM) which is unstable against the formation of one or more high-field domains when the biased field is above the NDM threshold field.⁹ In lock-on devices, because of the high resistance of the SI material, a large field can be maintained across the device before triggering. Once the device is triggered, the trigger-beam generated carriers cause high-field domains to form. In our model, the high field in the domain generates more carriers through impact ionization, and the device makes a transition to the lock-on state. The impact ionization within the high-field domain competes with the trapping effect of the deep levels, and interaction of these two processes determines the characteristics of the lock-on effect.

The filament conduction is necessary in lock-on devices to explain the voltage-limiter-like characteristic in the ON-state branch of the I-V curve. It is commonly accepted that CCNDR in the J-V curve of a device is unstable against the formation of filaments,¹⁴ and this leads to a voltage-limiter-like behavior in the I-V curve (bottom inset of Fig. 1). The

limiting voltage is determined by the minimum voltage in the NDR region of J-V curve, and the filament radius is determined by the device current. In our model, this limiting voltage is same as the lock-on voltage, and its experimentally observed characteristics are explained.

The higher lock-on field for InP (compared to that for GaAs) is, at least semi-quantitatively, explained in our model by the bandstructure difference in the two materials. In particular, the L-valley minimum of InP is ~ 0.53 eV above the Γ -valley minimum and is larger than the difference between the two minima in GaAs, which is ~ 0.31 eV. Consequently, the ratio of the NDM threshold field for InP to that for GaAs is ~ 3.3 .⁹ For the one case where it has been measured, the observed lock-on field for SI InP is larger than that for SI GaAs by a factor which depends on the measurement conditions and the type and density of defects in the GaAs material.³ In most cases, however, the factor is very similar to above ratio.

The effect of defect density on the lock-on voltage is explained within our model by noting its effects on carrier scattering and trapping. For SI materials, the density of neutral deep impurity centers is much larger than the density of trapped centers which are usually negatively charged. For neutral impurity scattering, the relaxation time is inversely proportional to the impurity density.¹⁵ With high defect density, therefore, the scattering relaxation time is short, and a large electric field is needed for carriers to attain enough energy to transfer to the satellite valley after collisions. In addition, the carrier trapping rate is directly proportional to the deep level density. Therefore, for materials with a high density of deep levels, a high field is needed to increase the impact ionization rate and balance the high trapping rate.¹⁰

Deep impurity scattering modifies the velocity-field relationship, and thus the mobility of the material. It is reasonable to assume that the low-field mobility would decrease and the NDM threshold field would increase with the increasing density of deep impurities. Incorporating this effect into our model, the NDM threshold field can be obtained once the

low-field mobility is known. For undoped GaAs the low-field mobility is $\sim 6000 \text{ cm}^2/\text{V}\cdot\text{s}$,¹⁶ and for GaAs:Cr, the low-field mobility is $\sim 4400 \text{ cm}^2/\text{V}\cdot\text{s}$.¹⁷ In our model, these mobilities respectively give predicted NDM threshold fields of 3.7 kV/cm and 5.1 kV/cm.¹⁰ These numbers are very similar to the observed lock-on fields for these two types of GaAs material. Ideally, measured low field mobilities for the same samples as used in the lock-on measurements should be used in the calculations, and this might alter slightly the above predicted fields. Since this is not possible, we have used mobilities from the literature^{16,17} in these initial calculations. Nevertheless, the similarity in the computed results and the observed lock-on fields should indicate that our model is at least semi-quantitatively correct.

The effect of the temperature on the lock-on field is related, in our model, to the temperature dependence of scattering mean free path. The mean free path increases as the temperature decreases. Thus, a low field is needed to scatter electrons to the satellite valley. It has been shown experimentally that for n-type GaAs the negative-differential-mobility (NDM) threshold field linearly decreases with temperature.¹⁸ The ratio of NDM threshold field at 300 K to that at 77 K is very similar to the ratio of corresponding lock-on fields at these temperatures.¹⁰

The requirement of a certain minimum bias field for triggering lock-on is related to the requirement of minimum concentration of carriers that must be generated initially before a domain can form and the device can make a transition to the lock-on state. This requirement affects the threshold behavior and not the lock-on field itself. With a low-power triggering beam, a large pre-trigger bias field is necessary to switch the device into lock-on since the impact-ionization generation rate, which is a function of carrier concentration and field, must be larger than the trapping rate.¹⁰ Otherwise, the device would operate in a photoconductive mode.

Some important conclusions pertaining to pulsed power switching can be made on the basis of our model. The most important of these is that since the TE effect is expected in

most direct gap semiconductors that have indirect gap minima with large effective masses, the lock-on effect should also occur in such materials. Semiconductors that have displayed the TE effect include GaAs, InP, CdTe, InAs, InSb, ZnSe, and many ternary and quaternary compounds. The lock-on effect must therefore be considered when using these materials in pulse power switching devices. Pulsed power switches—as distinct from other switches including fast, high voltage switches that transfer small energies—are required to hold off large voltages (≥ 1 kV), switch large currents (≥ 1 kA), and transfer large pulse energies to a load ($>$ several joules). In a typical application, a switch might be used to hold off 25 kV, switch a peak current of 5-10 kA, and transfer ~ 20 J of energy. It is often of importance that switches designed for such applications transfer energy efficiently—particularly when high repetition rates are required. The lock-on effect thus poses an intrinsic limitation for bulk (such as photoconductive) or bulk-type (such as a thyristor with a thick base required for high hold-off voltage) pulsed power switches based on materials where the TE effect can occur. For example, GaAs devices that are ≥ 100 μm thick may be expected to have a forward drop of ≥ 50 V, which will be excessive for many high current applications. Similar limitations may be expected for the other materials listed above. Thus, materials in which the TE effect can occur may not be suitable candidates for switching applications where low output impedance is required of the modulators.

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FIGURE CAPTIONS

Fig. 1. Typical profiles of current (the upper curve) and voltage (the lower curve) in a pulse-forming line switched with a GaAs opto-thyristor.⁶ In the ON state, the voltage across the device is ~ 100 volts, corresponding to a field of ~ 5 kV/cm. Top inset: A cross section of the GaAs opto-thyristor structure with Cr-doped, Bridgman grown, semi-insulating GaAs base layer. Bottom inset: Schematic representation of current-density vs. voltage (J-V) and current vs. voltage (I-V) curves of lock-on devices. The lock-on devices exhibit a current-controlled negative resistivity (CCNDR).

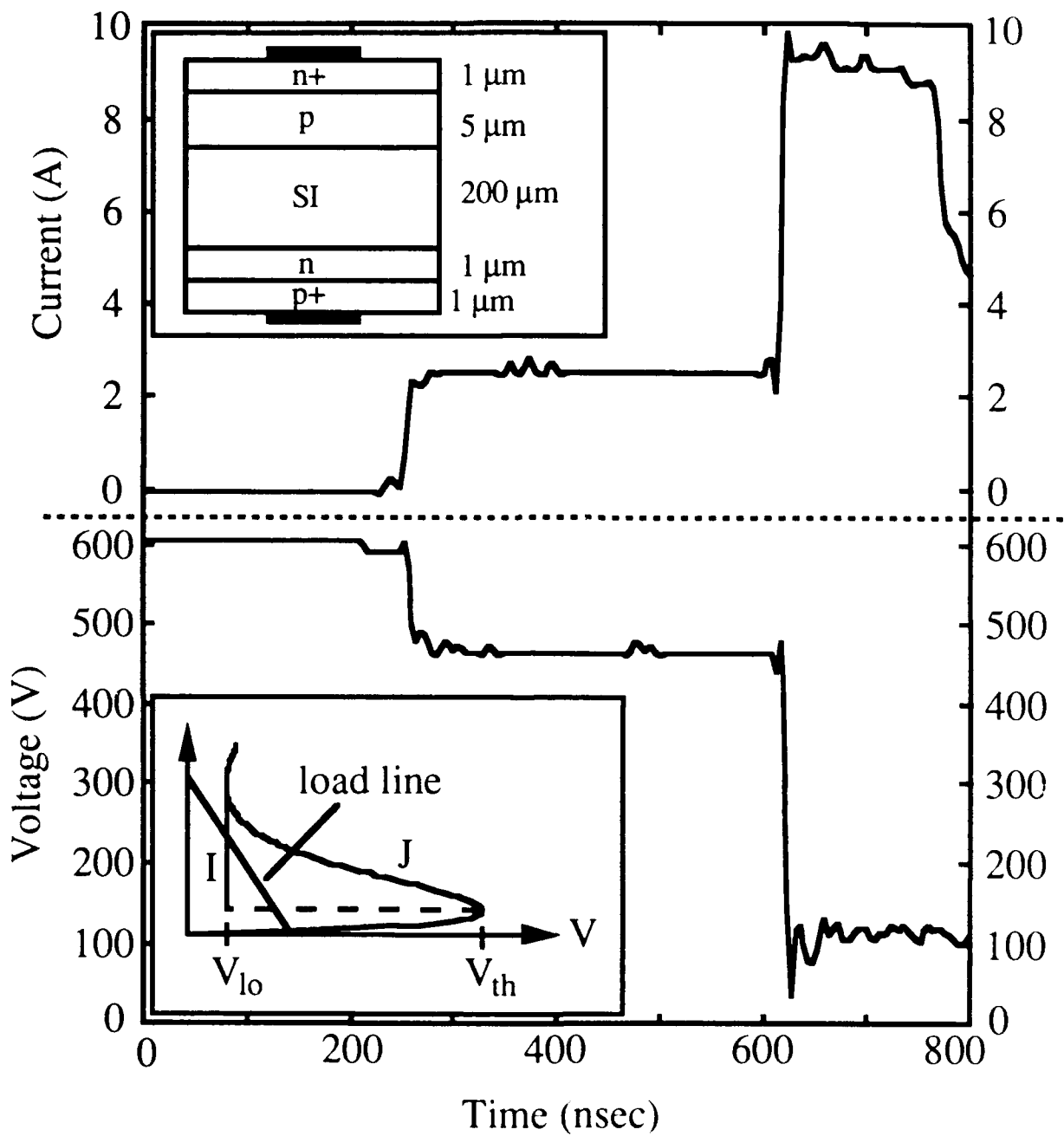


FIGURE 1. GUNDERSEN ET AL

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