Photon-activated charge domain in high-gain photoconductive switches

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We report our experimental observation of charge domain oscillation in semi-insulating GaAs photoconductive semiconductor switches (PCSSs). The high-gain PCSS is intrinsically a photon-activated charge domain device. It is the photon-activated carriers that satisfy the requirement of charge domain formation on carrier concentration and device length product of 10^{12} cm^{-2}. We also show that, because of the repeated process of domain formation, the domain travels with a compromised speed of electron saturation velocity and the speed of light. As a result, the transit time of charge domains in PCSS is much shorter than that of traditional Gunn domains.

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For many years, it has been accepted that Gunn domains cannot be formed in semi-insulating gallium arsenide (SI-GaAs) device. This is because the carrier concentration of SI-GaAs is too low to satisfy the condition of forming Gunn domains[1], in which a product of carrier concentration and device length (*nd* product) must be greater than 10^{12} cm^{-2}. In the past few years, however, researches on photoconductive semiconductor switch (PCSS) showed nonlinear characteristics[2–4] (also known as lock-on effect or high-gain mode), which can be found only in the III-V semiconductors such as gallium arsenide (GaAs) and indium phosphide (InP) under high electric field. The high-gain PCSS coincides with Gunn domain device in the following: (1) Lock-on happens only in semiconductors which show transfer-electron effect or negative differential resistance (NDR) effect, silicon PCSS does not show lock-on effect. (2) The lock-on field threshold is higher than that of Gunn electric field threshold (the threshold of NDR). These imply that Gunn domain should be formed inside PCSS if the *nd* product is greater than 10^{12} cm^{-2}. On the other hand, as PCSS is triggered by optical pulses, it is natural to think that the *nd* product can be fulfilled by optically generated carriers. So PCSS is possibly a photon-activated charge domain (PACD) device. Although photoconductive experiments have been done on transfer-electron device (TED)[5] and Gunn domain formation inside SI-GaAs has been conjectured[3], there is no experimental evidence so far to support PACD generation with *nd* product of less than 10^{12} cm^{-2}. In this letter, we would like to show our experimental observation of the PACDs in SI-GaAs PCSS for the first time. Which was similar to the Gunn domain under the action of the transferred electron effect in GaAs conduction band[6]. We will also show that it is due to the transfer-electron effect, avalanche breakdown, radiative recombination, photon absorption and electron-hole (e-h) regeneration that makes the PCSS turn on faster as if the carriers transverse the switch with a speed higher than the electron saturation velocity.

The semi-insulating PCSS used in our experiment had a resistivity of $> 5 \times 10^7$ ohm-cm in total darkness. The *nd* product was roughly 0.6×10^7 cm^{-2}, which is much less than the requirement of forming Gunn domains. A Nd:YAG frequency-doubled laser was used as the trigger. The laser operated at a wavelength of 532 nm with a pulse width of 200 ps, and the laser pulse energy ranged from μJ to mJ. The storage oscilloscope used was Tektronix 7934. A 60 dB coaxial attenuator with a bandwidth of 0 – 18 GHz was used between the PCSS and the oscilloscope, as shown in Fig. 1. As it is well known that there is a threshold condition for PCSS to work in the lock-on region. The lock-on threshold condition consists of a minimum electric field and a minimum triggering laser energy at this electric field. The lock-on threshold condition in our experiment is shown semi-logarithmically in Fig. 2 by plotting the electric bias field (linear) versus laser trigger energy (logarithmic). The solid dots are experimental data. The dashed line is a guiding line for the reader. The analytical equation of the guiding line is $y = 6.67 \times 10^{6-0.64x}$, where y is the laser energy in μJ, x is the biasing electric field in kV/cm. It is interesting to note that the threshold electric field and the threshold laser energy are exponentially related. To increase the electric field is more efficient than to increase the laser energy. The threshold condition is along the guiding line, which separates lock-on region (region I) and the linear region (region II). The requirement on the triggering laser energy is essential to fulfill the requirement of Gunn domain formation by generating enough carriers. The requirement on the electric field threshold is borne on the requirement of NDR threshold (Gunn threshold).

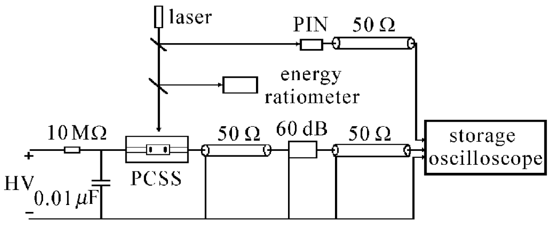

Fig. 1. Experimental setup of triggering PCSS's by 532-nm laser pulse.

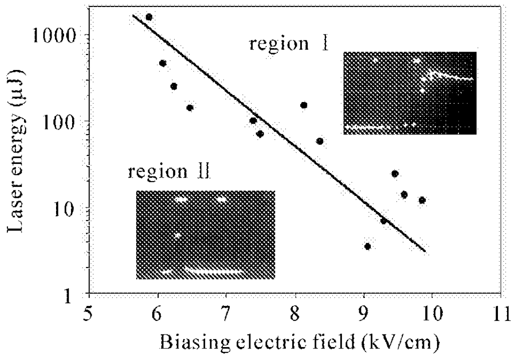

Fig. 2. Biasing electric field versus laser energy for the threshold condition.

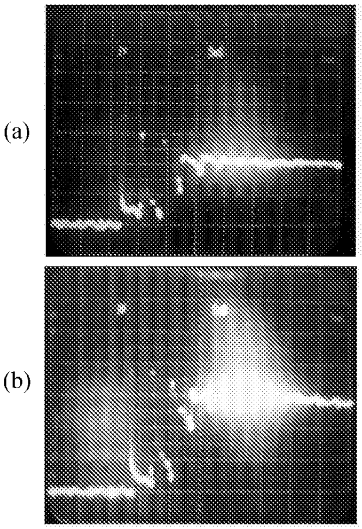

Fig. 3. The experimental current waveforms observed at two threshold conditions. The scales are 1 V/div for Y and 5 ns/div for X in both (a) and (b).

In our experiment, the electric field threshold of high-gain mode was from 6 to 10 kV/cm, which are higher than NDR threshold of GaAs.

At the threshold condition, current waveforms shown in Figs. 3(a) and (b) were observed. These two figures correspond to two different threshold conditions of (electric field, trigger energy) equal to (7.4 kV/cm, 56 μJ) and (9.6 kV/cm, 13.8 μJ) respectively. In Figs. 3(a) and (b), waveforms of repeated pulses can be clearly observed after the laser triggering. The intervals between two adjacent pulses keep unchanged and they are approximately 6.5 ns. The temporary current oscillation disappears gradually as large current density formed in the switch (PCSS turns into lock-on). With the falling edges of the current pulses rising continuously, conducting e-h plasma channels are gradually formed after several pulses (domains). Such kinds of pulsed current waveform cannot be found at region I and region II in Fig. 2, where the (electric field, trigger laser energy) pairs are away from the threshold condition. The oscillation current waveforms observed in Figs. 3(a) and (b) are clear indications of repeated charge domains formed in PCSS.

The PCSS used in our experiment had a *nd* product of 0.6×10^7 cm^{-2}, which is much less than 10^{12} cm^{-2}. It must be the laser trigger that generates enough e-h pairs to fulfill the Gunn threshold condition. Using a trigger laser energy of 13.8 μJ, the photo-generated carriers was calculated to be 3.7×10^9. The focusing laser beam had a diameter of roughly 0.15 mm. The absorption depth of GaAs was estimated to be 1 μm[9]. Then the photo-generated carrier concentration was calculated to be 2.1×10^{17} cm^{-3}. The integration of the carrier concentration over the device length is $\int_0^l n(x)\mathrm{d}x = 3.15 \times 10^{14}$ cm^{-2}, which is much bigger than 10^{12} cm^{-2}. Notice that the carrier recombination time (sub-nanosecond order of magnitude[10]) is much longer than the Gunn domain growth time (picosecond order of magnitude[9]) in GaAs. So photo-generated carriers should have the same effect with intrinsic carriers in forming charge domains. In other words, it is photo-generated carriers that supplied enough carriers to form the Gunn domain. The SI-GaAs PCSS is essentially a PACD device.

The Gunn domain formation inside the PACD device is much more complicate compared to traditional Gunn domain device. It involves various effects such as photo generation of carriers, electron transfer effect, carrier avalanche multiplication, carrier radiative recombination and photon absorption[7,8]. Strong radiative recombination has been varified experimentally by current filaments measurements[3]. Let's examine PCSS working in the linear region, lock-on region and the threshold region respectively using the concept of PACD.

(1) Linear region: region II in Fig. 2.

(a) The electric field is higher than the Gunn threshold and the laser energy is not high enough to generate a *nd* product greater than 10^{12} cm^{-2}. Under this situation, charge moves similar to accumulation-layer mode in traditional TED are formed[1].

(b) The electric field is lower than the Gunn threshold. Due to the low electric field, there is no electron transfer effect. But the device still generates a pulse due to photoconductive effect.

(2) Lock-on region: region I in Fig. 2. When the laser energy is higher than the triggering laser energy threshold and the bias field is also higher than the NDR threshold, the field strength inside the charge domain increases rapidly to the avalanche breakdown of GaAs materials at the domain nucleation and growth period. Intense impact ionization happens and the number of carriers increases nonlinearly through avalanche process[7]. Photons are emitted through radiative recombination accompanying the impact ionization. These photons propagate at a speed of about 10^9 cm/s in GaAs, surpassing the avalanche ionization region, and being absorbed again. If the electric field of photon absorption region is still higher than the threshold of NDR, new high field charge domain is triggered again in the absorption region. The new domain will trigger new avalanche impact ionization again. Because of this repeated process of domain formation, avalanche impact ionization, radiative recombination, photon absorption and e-h generation, an e-h plasma channel is quickly formed between cathode and anode to turn on the switch.

(3) Threshold region: along the guiding line in Fig. 2. Under threshold triggering condition, charge domain can be generated, but the electric field inside the domain

is lower than the intrinsic breakdown threshold. There is only one domain inside the switch at the beginning. The transit time of this single domain, which is similar to the domains in lock-on region, is determined by the both the electron saturation velocity and speed of light in GaAs. Later the PCSS can either run into lock-on or be turned off after generating a pulse string. But from our experiment, the switch tends to run into lock-on rather than being turned off (refer to Fig. 2). Due to the pulse string, the switch cannot be turned on rapidly. The oscillation waveforms as shown in Figs. 2(a) and (b) can only be clearly observed in this region. This is probably the reason why Gunn domain oscillations have not been observed before. It is quite interesting to note that, the current waveforms observed in Figs. 2(a) and (b) match the triangle domains proposed by Bosch and Engelmann[9] well.

As it is well known that the impact ionization rate is more than exponentially proportional to the reciprocal electric field for GaAs[1]. And the photon radiation rate is proportional to the excess non-equilibrium carrier density. So radiative recombination increases with increasing impact ionization inside the domain. Some of the emitted photons are absorbed by GaAs again. The absorption of these photons is strong in high field region (inside domain) and weak in low field region (outside domain) due to Franz-Keldysh effect[10]. The photo-ionization due to the absorption of photons has the same distribution pattern as the photon absorption. Therefore, the photo-ionization inside the domain is much stronger than that outside the domain. But since the photon travels at a higher speed than that of electron, the domain appears moving faster than the saturation velocity of electrons.

So, the carriers across the gap of switches' electrodes were pro rata by speed of light and speed of electron saturation velocity. Take the electron saturation velocity of GaAs as 10^7 cm/s[1], and the speed of light in GaAs as 10^9 cm/s (refractive index of semi-insulating GaAs was 5.025 at 0.55 μm), the speed of photos are 100 times faster than the speed of electron saturation velocity. Then we have

$$\frac{S_\mathrm{e}}{S_\mathrm{p}} = \frac{1}{100}, \tag{1}$$

$$S_\mathrm{e} + S_\mathrm{p} = L, \tag{2}$$

where $L = 3$ mm is the gap between the two electrodes, S_e is the distance travelled by electrons, S_p is the distance travelled by photons. The transit time t_d of the switch, i.e., the time for a domain to transverse the switch can be expressed as

$$t_\mathrm{d} = \frac{S_\mathrm{e}}{v_\mathrm{s}} + \frac{S_\mathrm{p}}{c} \tag{3}$$

where v_s is the saturation velocity of electrons, c is the speed of light in GaAs. The first term and the second term on the right hand side of Eq. (3) correspond to the transportation of electrons and photons respectively. Equation (3) is also the time for carriers across a gap of switches' electrodes. Take the electron saturation velocity of GaAs as 10^7 cm/s[1], and the speed of light in GaAs as 10^9 cm/s, the transit time was calculated as t_d=0.53 ns. So the domain traversed the gap at an average speed of $\overline{v} = \frac{L}{t_\mathrm{d}} = 5.66 \times 10^8$ cm/s. So the theoretical value matches the experimental result well. This result shows that the domain traverses the switch at the speed of about 10^8 cm/s rather than the saturation velocity of electron. This speed is one order of magnitude higher than the saturation drift velocity of electrons under high field. This abnormal phenomenon has also been experimentally observed by other researchers[3].

In conclusion, we have observed the PACD experimentally in SI-GaAs PCSS at the lock-on threshold condition. The high-gain GaAs PCSS is essentially a type of PACD device. The PACD can only be clearly observed near threshold conditions of lock-on mode. In deep lock-on, a lot of Gunn domains co-exist in the switch resulting in a sharp turn on. The oscillating waveforms are hard to be observed.

The requirement to form Gunn domains on carrier concentration (n) and device length (l) product of $nl > 10^{12}$ cm^{-2} should be modified to $\int_0^l (n+n')\mathrm{d}x \geq 10^{12}$ cm^{-2}, n' is the photo-generated (or by other means) carrier concentration. The former requirement is just a plenary condition to form Gunn domains, while the later one is the plenary and necessary condition. In another words, the former is a narrow sense condition and the latter is the generalized condition of forming Gunn domains.

In PACD devices such as GaAs PCSS in lock-on mode, transfer-electron effect, avalanche breakdown, radiative recombination, photon absorption and e-h regeneration happen inside the Gunn domain. Over the path that the domain travels, part of it is by the speed of light, which is one order of magnitude higher than the saturation velocity of electrons. This makes the switch turn on faster as if the electron transverses the switch with a speed higher than its saturation velocity.

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