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High Current Operation of a Semi-insulating Gallium Arsenide Photoconductive Semiconductor Switch Triggering a Spark Gap *

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A transient peak current as high as 5.6 kA is obtained by a GaAs photoconductive semiconductor switch (PCSS) in series with a spark gap. Based on the characteristics of the GaAs PCSS, mechanisms of discharge between the PCSS and the spark gap are discussed. It is implied that a hybrid operation mode of photo-activated charge domain occurs due to the superposition of the bias voltage and the instantaneous radio frequency voltage.

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Photoconductive semiconductor switches have been used in a range of applications such as compact particle beam accelerators, ground penetrating radar, fast gated cameras and optically activated firesets. Due to their unique characteristics, high power semi-insulating gallium arsenide photoconductive semiconductor switches (SI GaAs PCSS) have been developed considerably, and are similar to three-terminal semiconductor devices. The primary characteristics of GaAs PCSS are their low inductance and capacitance, and high-speed response to laser pulses.[1,2] According to the behavior of GaAs PCSS, the photo-activated charge domain (PACD) model for a high gain GaAs photoconductive switch was proposed and demonstrated.[4,5] In a proper configuration, such a switch shows an ultrafast risetime, of the order of 1 ps with very little jitter.[6] However, pulsed power and high voltage applications require switches that can withstand high current density. In those photoconductive operations, a spark gap is used,[7–9] but the intensity of current switched is lower. As shown in Fig. 1, in our experiments the GaAs PCSS is in series with an atmospheric air spark gap, which is a tiny gap (0.6 mm) in the coaxial transmission line structure. The resistivity of the GaAs material is larger than $5 \times 10^7\,\Omega$/cm, and the mobility is larger than $5500\,\mathrm{cm}^2/\mathrm{V{\cdot}s}$. Multilayer transparent dielectrics as passivation and insulation protection materials are deposited and coated on the surface of the photoconductive switches. The Au/Ge/Ni electrodes form an ohmic contact by using a standard mixture of Ni/Au-Ge/Au for the metallization at 450°C and the thickness is 700 nm. The electrode distance of the GaAs PCSS is 3 mm. The plane size of the electrode is 6.0 mm × 3.0 mm. The Nd-YAG nanosecond laser is used to trigger the SI GaAs PCSS, the wavelength of the trigger laser is 532 nm and the time duration of the laser pulse is 3.5 ns. A sampling resistor of 0.1 Ω is in series with the PCSS and spark gap. A Lecroy oscillograph (6G) is in parallel with the resistor to detect the voltage after attenuation by a 40 dB coaxial attenuator. The bias voltage is increased to 4 kV gradually from 2 kV as the energy of the trigger laser is maintained at 1.8 mJ. The widths of each pulse remain unchanged and they are approximately about 5 ns, as shown in Fig. 2, and the peak current exceeds 5.6 kA.

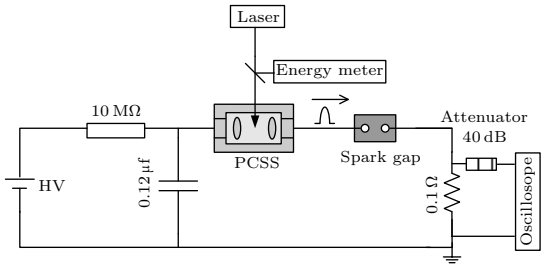

Fig. 1. Schematic diagram of the testing circuit.

As we all know, there are two principal modes of operation that result in oscillation for GaAs transferred electron devices. One is called the transit time mode or Gunn domain mode which has a low efficiency of power generation, the other is resonant mode.[10–12] According to the semi-insulating GaAs PCSS, in this Letter, a photo-activated charge domain model GaAs PCSS is proposed and demonstrated for a nonlinear mode. Using the trigger laser energy of 1.8 mJ, the

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focusing laser beam has a diameter of roughly 3 mm and the absorption depth of GaAs is estimated to be 1 μm,[4,5,13] the photo-generated carrier concentration is calculated to be about $6.9 \times 10^{19}/\mathrm{cm}^3$, so that the integration of carrier concentration n over the device length l is much larger than the Gunn domain condition:

$$\int_0^l n(x)dx > 10^{12}/\mathrm{cm}^2. \tag{1}$$

In other words, these are the conditions to give rise to the forming of the photo-activated charge domain.[3–5]

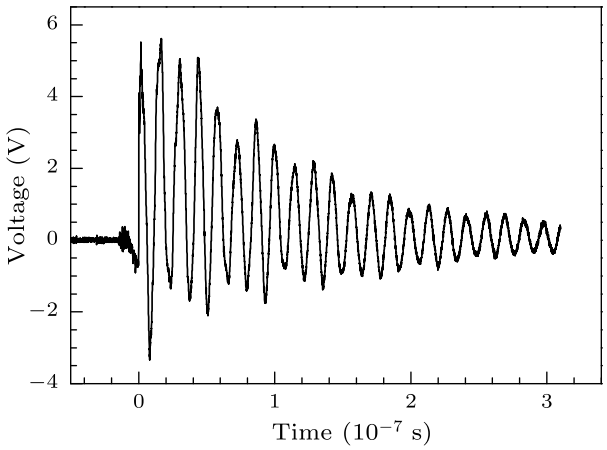

Fig. 2. Output waveform from PCSS at the bias voltage of 4 kV triggered by 1.8 mJ laser.

In our experimental setup, before the PCSS is triggered by the laser, the GaAs semiconductor tends to capture most of the bias voltage, which is approximately 4 kV. The bias electric field is about 13.3 kV/cm, which is over two times as large as the threshold electric field E_T (3.2–4.2 kV/cm) required for negative differential resistance, which results in building up of the photon-activated charge domain. The delay time of the GaAs PCSS can be described by

$$t_c = (\ln n_c - \ln n)/(v_d \alpha_{\mathrm{eff}}), \tag{2}$$

where t_c denotes the delay time, n_c is critical carrier concentration, n is the photo-generated carrier concentration, v_d is the average drift velocity of the electrons inside the domain, α_{eff} is the effective coefficient impact ionization. At the critical state of $n = 10^{17}\,\mathrm{cm}^{-3}$, $n_c = 10^{24}\,\mathrm{cm}^{-3}$, $v_d = 10^7\,\mathrm{cm/s}$, we can obtain $t_c = 1.48$ ns based on Eq. (2). The rising time of the output electrical pulse which triggers the spark gap is about 1.29 ns. The switch-off causes an ultra-fast rising pulse with a magnitude of nanoseconds to propagate toward the spark gap. The transient voltage upon the spark gap creates the highly distorted electric field resulting from a higher overvoltage compared with the breakdown voltage of atmospheric air (30 kV/cm). The whole physical process can be described as follows.

(1) When the triggering conditions are satisfied, the PCSS begins to oscillate that gives rise to the first PACD cycle of the waveform,[14] as shown in Fig. 2, which lasts about 5 ns. The transit process provides a very high voltage gradient (dV/dt) required for low jitter triggering of the spark gap. The formative time, defined as the onset time for sensible current flow in the circuit, is about 0.4 ns with approximately 2-ns-rise-time incident pulse.[15] Subsequently, the current rises rapidly to about 80% of the current which would generate when the gap become conductive. The gradient of the current is thereafter much sharper and the oscillation of the current caused by the discharging of the spark gap with a magnitude of nanoseconds induces an instantaneous rf field presented in the semiconductor switch.

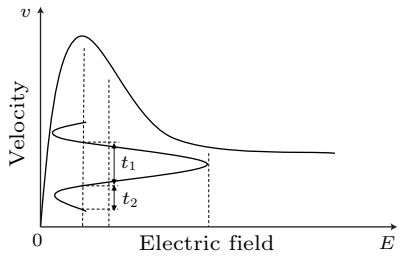

Fig. 3. $E - V$ characteristic curve of PACD.

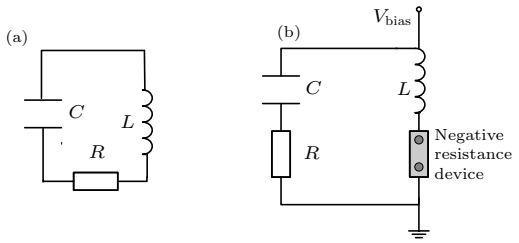

Fig. 4. (a) Simple resonant circuit (b) Circuit including a negative resistance device (a) Simple resonant circuit (b) Circuit including a negative resistance device

(2) Since the carrier recombination time (in tens of nanoseconds) in the GaAs device is much longer than the generation time of the plasma channel of the overvoltaged spark gap, when the spark gap is discharging, the photo-generated carriers within GaAs still exist for several nanoseconds or more, which means that GaAs must be on the negative differential resistance portion of its characteristic. Thus, following the discharging of the spark gap and the recombination of the photo-generated carriers, the carrier concentration decreases from the order of magnitude of $10^{19}\,\mathrm{cm}^{-3}$ and the frequency of the resonant circuit is changing dynamically. When the rf electric field is high enough to swing below the critical voltage level to prevent space charge from building up within the device, PACD cannot form. In this case, the rf amplitude is large enough to swing the voltage below the critical level during part of each cycle, and the carriers in the device con-

tribute directly to the conversion of power from dc to rf. Figure 3 is the characteristic curve of velocity of carriers versus electric field, during every rf cycle, time t_1 should be less than the growth time of PACD, while time t_2 should be greater than the relaxation time of PACD to allow the space charge to disappear or discharge.

(3) If the velocity of the space charge across the PCSS is the saturation velocity of the electron (10^7 cm/s), the transit time that the charge domain transits the gap of electrodes is about 30 ns. As shown in Fig. 2, the cycle of current oscillation is about 11 ns, which is smaller than the transit time. Therefore, the mode of the space charge domain is not the transit time mode. Such a type of behaviour has considered the interaction between the transit oscillation similar to the Gunn device and the oscillation of the external resonant circuit. The fully formed domain is discharged or "quenched" before it reaches the anode because the period of the rf oscillation is smaller than the transit time of a full domain. Thus it can be named the "hybrid mode" of PACD, the operation has partly a Gunn and partly a quenched domain character. However, the output current cannot oscillate without limiting. According to the resonant circuit theory, as shown in Fig. 4, the current variations take the form

$$i(t) = \exp(\alpha t)\exp(j\omega t), \tag{3}$$

where $\alpha = -R/2L$, $\omega = \left|\sqrt{R^2 - 4L/C}/2L\right|$. In each case the current will oscillate sinusoidally with the angular frequency ω, and the amplitude of the oscillation varies exponentially with time in a way which depends upon the resistance of the circuit. In our circuit, the equivalent resistance is dynamic. When GaAs is on the negative resistance portion of its characteristic, the dynamic resistance is negative, implying that α is positive and the oscillation amplitude or energy grows exponentially with time. After about 16 ns, as shown in Fig. 2, however, the amplitude begins to decrease, which means that the circuit resistance will have a positive value and α is negative. The energy is dissipated with time by the circuit.

In conclusion, we have observed the oscillation of PACD experimentally in an SI GaAs PCSS in series with an air spark gap at the nonlinear mode condition and a current as high as 5.6 kA is obtained, which offers significant benefits over the traditional electrical or optical trigger generators. The mechanism of current oscillations in the SI GaAs PCSS has been analysed. The PACD is formed chiefly by the photogenerated carriers, and quenched periodically by the influence of superposition of the bias voltage and the rf voltage. Furthermore, it is also proved that a GaAs PCSS is really a type of photo-activated charge domain device.

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