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Velocity of current filament at the high gain mode of GaAs power photoconductive switches

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ABSTRACT

Many of the characteristics, especially transient turn-on, of high gain mode photoconductive semiconductor switches can be explained by a model similar to a gas streamer model in this paper. Based on the gas discharge theory and photoactivated charge domain model, the mechanism of current filament at the high gain mode of GaAs photoconductive semiconductor switches (PCSSs) was discussed. It is pointed out that both the carrier density and the regional electric field satisfy two critical conditions for the formation and development of streamers. Experimental phenomena indicate that the turn-on time is considerably shorter than the time required for the transit of carriers crossing the electrode gap of the device at saturation transfer velocity. Moreover, the transient turn-on characteristic was analyzed and the ultra-fast velocity of current filament was calculated. The calculated results are in agreement with the experimental results.

1. Introduction

Photoconductive semiconductor switches (PCSSs) are often used as high-speed electronic switches [1]. PCSSs demonstrate many advantages such as high power, fast switching speed, small parasitic capacitance, high repetition frequency, and jitter-free operation. In particular, the III–V compound PCSSs have demonstrated two operation modes and a fast response within picosecond range [2].

Published theories that describe high gain photoconductive switching, however, are incomplete or inconsistent with experimental measurements. Several models have explained the steady-state conduction characteristics [3–8], but most of them lack the essential ability to describe the filament current velocity larger than the saturated carrier drift velocity as is observed experimentally [9]. In the past few years, streamer theory has been proposed to explain the filament current in PCSSs [10–13]; however, the description of steamer formation conditions and the characteristics of the filament current are lacking. In this paper, the streamer model combining photoactivated charge domain theory with the streamer mode can be employed to explain the mechanism of nonlinear phenomena of PCSSs such as lock-on effect and the current filament [14].

2. Experimental setup

In our experiments, the photoconductive material used for the PCSSs is SI-GaAs with the dark resistivity of $\rho \geq 5 \times 10^7$ Ω cm. The electron mobility μ is higher than 5000 cm^2/V s. Intrinsic breakdown electric field of SI-GaAs is larger than 250 kV/cm. The carrier density n is about 10^{14} cm^{-3}. The overall size of the GaAs wafer is 8.0 mm (wide) × 10.0 mm (long) × 0.6 mm (thick). The size of each electrode is 6.0 mm × 3.0 mm, and its radius of rounded angle is 1.1 mm. Multi-layer transparent dielectrics used for the passivation and insulation protection materials were deposited and coated on the surface of the PCSSs. The switch was placed on a Teflon substrate with planar transmission lines and connected with external circuit by coaxial transmission lines.

The YAG nanosecond laser operated at the pulse duration of 3.5 ns and energy of 1.8 mJ per pulse was used in the experiment. The circuit for the experiment is shown in Fig. 1. When both of the biased voltage and the energy of laser were higher than the threshold requirements of high-gain mode, PCSSs could work at the nonlinear mode. The nonlinear waveform of GaAs PCSSs biased at 2.75 kV/cm is shown in Fig. 2. Once PCSSs were triggered, GaAs PCSSs would keep lock-on state until the electrical field on the switch dropped to 4–6 kV/cm [15]. The highest peak current of 38 A with the rise time of 1.086 ns was obtained when the PCSSs were biased at 2.75 kV/cm. The lasting time of lock-on state was longer than 1600 ns, which could damage GaAs PCSSs. The longevity of PCSSs in the nonlinear mode was shorter than that in the linear mode, and the repetition rate of pulse in the nonlinear mode were lower than that in the linear mode [16].

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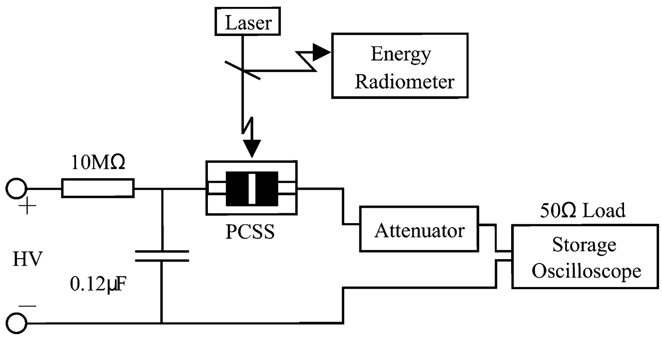

Fig. 1. Schematic diagram of circuit for experiment of PCSSs.

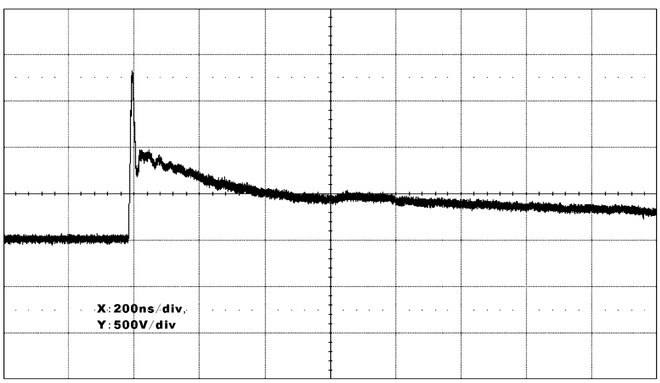

Fig. 2. Nonlinear waveform of PCSSs biased at 2.72 kV/cm.

3. Filament current

The high-field domain in the semiconductor must comply with the following formula:

$$n \times L > 1 \times 10^{12}\,\mathrm{cm}^{-2} \tag{1}$$

here n is the electron concentration and L is the length of the device. Eq. (1) denotes the essential conditions of forming stable charge domain required for the material characteristic and geometry of the device. In GaAs PCSSs, because the carrier density is too low to satisfy the condition of domain formation, it has been accepted that the Gunn domain cannot be formed in GaAs device for many years [17]. Noticing that the carrier recombination time (subnanosecond order of magnitude [18]) is much larger than the Gunn domain growth time (picosecond order of magnitude [19]). Therefore photogenerated carriers should have the same effect as the intrinsic carriers in the forming of the Gunn domain. However, under the condition of high trigger light, the electron concentration (n) includes photogenerated carrier concentration (n_p) and the intrinsic carrier (n_0) density. Therefore, the Eq. (1) is modified as

$$(n_p + n_0)L > 1 \times 10^{12}\,\mathrm{cm}^{-2} \tag{2}$$

Since the absorption depth of GaAs is about a millimeter at 1064 nm wavelength [20], when the energy of the trigger laser was 0.2 mJ, there were 1.0×10^{15} photogenerated carriers generating in the PCSSs. The focused laser beam had a diameter of 0.15 mm. Then the concentration of the photogenerated carriers was calculated to be on the order of $1.0 \times 10^{19}\,\mathrm{cm}^{-3}$. The integration along the device length was $(n_p+n_0)L = 1.5 \times 10^{17}\,\mathrm{cm}^{-2}$, which is much bigger than the criterion of $1 \times 10^{12}\,\mathrm{cm}^{-2}$ and the Gunn domain can be formed in GaAs device.

If the diffusion of the electrons is neglected, then the average photogenerated carrier concentration n_a can be calculated to be

$$n_a = \frac{N}{DhL} = 2.8 \times 10^{18}\,\mathrm{cm}^{-3} \tag{3}$$

where N is the number of photogenerated carriers, D is the diameter of the focused laser beam, and h is the absorption depth of GaAs material for the 1064 nm laser. Since the absorption depth of GaAs is greater than the wafer thickness, here h equals to 0.6 mm. For triangular domains, when diffusion is neglected, the maximum electric field of the domain E_m can be expressed by the Eq. (4) [18].

$$E_m = E_e + n_a(e/\varepsilon)b \tag{4}$$

where E_e and b represent the external electric field of the domain and the domain width, respectively, ε ($1.17 \times 10^{-10}\,\mathrm{C^2\,N^{-1}\,m^{-2}}$) is the dielectric constant of GaAs, and e (1.6×10^{-19} C) is the charge of a single electron. The schematic of the triangular domains is shown in Fig. 3. Here we define the value of E_e to be equal to the lock-on field and the width of domain to be 0.1 μm [21]; thereupon from Eq. (4), the maximum electric field of domain (E_m) is $4.7 \times 10^3\,\mathrm{kV\,cm^{-1}}$, which is much larger than the ideal GaAs avalanche breakdown field of 250 kV/cm.

At the high gain mode, threshold conditions of the primary streamer formation are determined by the following two factors: one is the carrier density, which should be not less than $10^{17}\,\mathrm{cm}^{-3}$ [22]; another is that the regional electric field of the streamer formation should be higher than the field at which the carrier impact ionization can occur in GaAs. After the photoactivated charge domain formed, the photogenerated carrier concentration n_a is much larger than $10^{17}\,\mathrm{cm}^{-3}$ and the maximum electric field of domain E_m is much larger than 250 kV/cm. From these calculated results, the trigger light provides the high carrier concentration, and the photoactivated charge domain offers the high electric field for the primary streamer formation. That is, the photoactivated charge domain and the photoproduction carrier initiate avalanche breakdown in the photogenerated region causing the transition from the photoactivated charge domain to streamer mechanisms to occur.

The body of the streamer is composed of electron–hole plasma and the carrier density reaches the order of $10^{17}\,\mathrm{cm}^{-3}$, so there are strong emission and radiation recombinations in this region. In addition, this region is formed by the electron–hole plasma, so the electric field strength is lower than that of other regions. According to the Moss–Burstein effect, the finite absorption wavelength shifts to the short-wave direction of about 20–97 nm, and the photon can easily pass through this area. The body of the streamer can be regarded as a motive light source

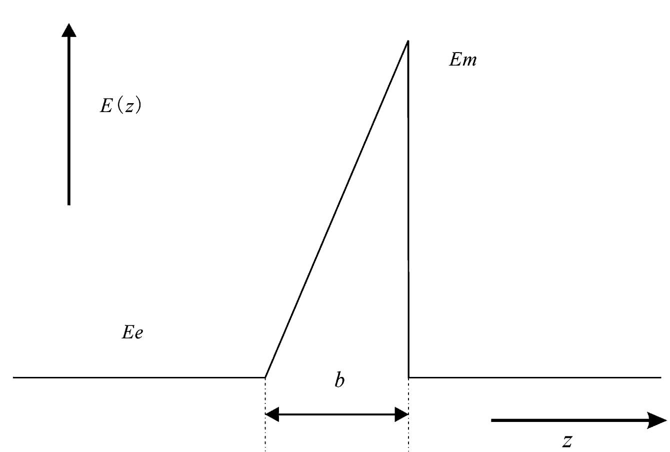

Fig. 3. Field distribution of growing domain (triangle domain).