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Multiple charge domains model for the lock-on effect in GaAs power photoconductive switches

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Abstract

This paper reports that the lock-on field of semi-insulating (SI) GaAs photoconductive semiconductor switches (PCSSs) was measured under different bias voltages. Based on the experimental results and the transferred-electron effect, a model for the lock-on effect in GaAs PCSSs is proposed. It is shown that the charge domain with an ultrahigh electric field is due to a high photogenerated carrier density, which gives rise to intensive impact ionization accompanied by electron–hole recombination radiation within the domain. Since new domains can be nucleated uninterruptedly by the carriers generated by absorption of recombination radiation, the forefront domain crosses the switch at a speed alternating between the photon velocity and the carrier saturated drift velocity, which makes the observed velocity of carriers larger than the saturated drift velocity. The lock-on field results from the fixed number of a moving train of avalanching charge domains, the steady-state domains electric fields and the steadfast external electric field of the domains. The recovery of the lock-on effect is caused by domain quenching. The calculations agree with the experimental results. Moreover, the analytical results indicate that SI-GaAs PCSS is essentially a type of photo-activated charge domain device.

1. Introduction

Compared with conventional devices such as spark gaps or thyratrons, photoconductive semiconductor switches (PCSSs) exhibit a better rise time and jitter characteristics [1–3]; thus, these switches have been widely used in ultrahigh speed electronics, the field of high power microwave generation, pulse forming and the generation of THz radiation [4–10]. Because of many superior electrical characteristics, semi-insulating (SI) GaAs is preferred over other photoconductive materials in most pulse-power generation circuitry [11].

Generally SI-GaAs PCSSs can operate in two different modes. At low bias electric fields (below $3.5\,\mathrm{kV\,cm^{-1}}$), SI-GaAs PCSSs operate in the linear mode in which each absorbed photon generates at most one electron–hole pair. In contrast, above $3.5–8\,\mathrm{kV\,cm^{-1}}$ (depending on the type of GaAs), the device can be optically triggered into a sustained 'on' state, called lock-on' (also known as the high gain or nonlinear mode) [12]. The average electric field in this lock-on state is called the lock-on field and is independent of the device length, bias voltage, triggering optical energy and load resistance. When the PCSS operates in the lock-on state, the observed switch closure time is much shorter than the time for carriers moving at the saturated drift velocity to cross the switch, and due to carrier multiplication induced by a high field, the amount of triggering optical energy required is reduced by five orders of magnitude [13].

Until now, several models have been proposed to explain the lock-on effect [14–16]. However, the mechanism of the lock-on effect has not well been understood to date due to the great complexity of the dynamics of carriers in GaAs under high electric fields [17, 18]. In this paper, the lock-on field of SI-GaAs was measured under different bias voltages. Based on the experimental results, a model for the lock-on effect in GaAs PCSSs is proposed, and using the results from the model, the salient features of the lock-on effect are explained.

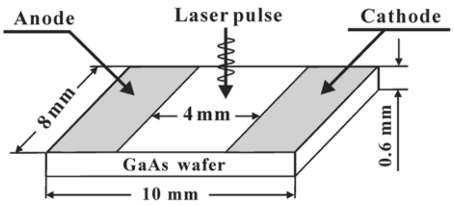

Figure 1. The schematic of a lateral PCSS.

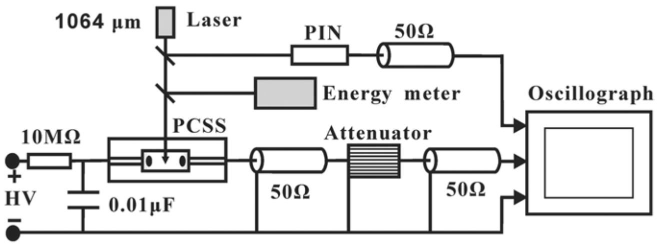

Figure 2. The experimental setup for the lateral PCSS.

2. Experiment

In our experiment, the photoconductive material used for the PCSSs was SI-GaAs with a dopant density of 1.5×10^7 cm^{-3}. The resistivity in total darkness was $>5 \times 10^7\ \Omega$ cm, and the mobility was larger than 5500 cm^2 (V s)$^{-1}$. The overall size of the GaAs wafer was 8 mm wide × 10 mm long × 0.6 mm thick. Using the electron beam evaporation technique, Au/Ge/Ni alloy electrodes were deposited on top of the photoconductive material and ohmic contacts were made by the annealing heat treatment. The electrode dimensions were 8×3 mm^2, and the length of the two electrodes was 4 mm. The geometry of the PCSS is shown in figure 1. The GaAs was placed on the substrate of the copper board with a transmission line, and the transmission line was connected from outside with two coaxial connectors. The light source used to excite the PCSS was a neodymium-doped yttrium aluminium garnet nanosecond laser that produced a 5 ns full width at half-maximum laser pulse at 1064 nm wavelength. The storage oscilloscope used was an Lecory-8500A, and a 60 dB coaxial attenuator with a bandwidth of 0–18 GHz was used between the PCSS and the oscilloscope. The experimental setup is shown in figure 2.

When the bias was 3.0 kV corresponding to the bias electric field of 7.5 kV cm^{-1} and triggering optical pulse energy was 0.5 mJ, a nonlinear current wave form of the PCSS was observed. The nonlinear wave forms superposed one hundred times are shown in figure 3(*a*). Figures 3(*b*) and (*c*) show twenty times superposed nonlinear wave forms at biases of 3.5 kV and 4.0 kV, respectively. From figure 3, we can observe that the output voltage increases as the bias increases; however, the difference between the bias voltage and the output voltage remains invariable; namely, the lock-on field of the PCSS is fixed at a constant value and independent of the initial biases. Table 1 shows the relation of the bias voltage and the output voltage. From table 1, we can conclude that the lock-on field of the PCSS is about 6.3 kV cm^{-1}, which is much larger than the Gunn threshold electric field.

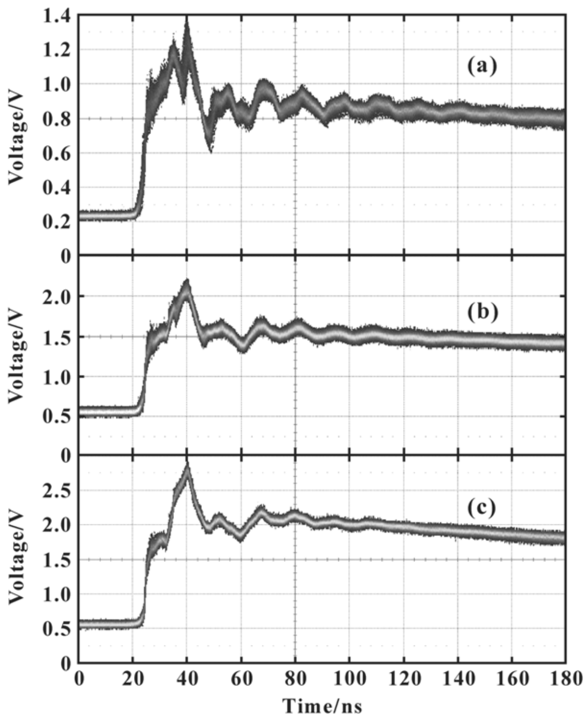

Figure 3. The nonlinear wave forms of the lateral PCSS at different biases: (*a*) one hundred times superposed nonlinear wave forms at a bias of 3.0 kV, (*b*) twenty times superposed nonlinear wave forms at a bias of 3.5 kV and (*c*) twenty times superposed nonlinear wave forms at a bias of 4.0 kV.

Table 1. The relation of the bias voltage and the output voltage and the corresponding lock-on field.

Bias voltage (kV)	Output voltage (kV)	Lock-on voltage (kV)	Lock-on field (kV cm^{-1})
3.0	0.6	2.4	6.0
3.5	0.9	2.6	6.5
4.0	1.4	2.6	6.5

3. Multiple charge domains model

Since the impurity absorption depth of GaAs is about a millimetre order of magnitude at 1064 nm wavelength [19], the triggering optical energy of 0.5 mJ absorbed by the PCSS with the thickness of 0.6 mm is about 0.2 mJ. Therefore, there are 1.0×10^{15} photogenerated carriers generating in the PCSS. The focused laser beam has a diameter of 0.15 mm. Then the concentration of the photogenerated carriers was calculated to be on the order of 1.0×10^{19} cm^{-3}. The integration along the device length was $\int_0^L n(x) \cdot \mathrm{d}x = 1.5 \times 10^{17}$ cm^{-2}, which is much bigger than the criterion of 1×10^{12} cm^{-2} given by Kroemer [20]. Due to the lock-on field always being larger than the Gunn threshold electric field, there must be a space charge domain generated in the bulk of the PCSS. If the diffusion of the electrons is neglected, then the average photogenerated carrier concentration n_a can be calculated to be

$$n_{\mathrm{a}} = \frac{N}{D \cdot d \cdot L} = 2.8 \times 10^{18}\ \mathrm{cm}^{-3}, \tag{1}$$

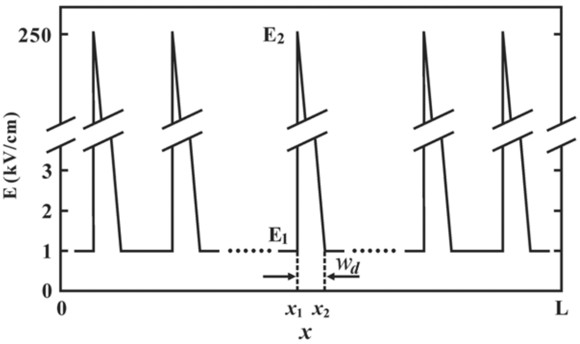

Figure 4. The schematic of multiple charge domains with a triangular shape.

where N is the number of photogenerated carriers, D is the diameter of the focused laser beam, d is the thickness of the PCSS and L is the length of the two contacts. For triangular domains when diffusion is neglected, the domain width w_d can be written as [21]

$$w_\mathrm{d} = \frac{\varepsilon}{en_\mathrm{a}}(E_2 - E_1), \qquad (2)$$

where E_1 and E_2 represent the external electric field of the domain and the maximum electric field of the domain, respectively, $\varepsilon = 1.17 \times 10^{-10}\,\mathrm{C^2\,N^{-1}m^{-2}}$ is the dielectric constant of GaAs and $e = 1.6 \times 10^{-19}\,\mathrm{C}$ is the charge of a single electron. The schematic of the triangular domains is shown in figure 4. Here we define the value of E_1 to be equal to the lock-on field and the width of domain to be 0.1 μm [22]; thereupon from (2), the maximum electric field of domain can be calculated to be $E_2 = 3.8 \times 10^3\,\mathrm{kV\,cm^{-1}}$, which is much larger than the ideal GaAs avalanche breakdown field of 250 $\mathrm{kV\,cm^{-1}}$. Thus, it can be seen that the stronger impact ionization must be a significant process within the optically activated charge domain

After the process of strong impact ionization, recombination immediately begins. In direct band-gap semiconductors, band-to-band recombination usually produces a photon having band-gap energy. This photon can be reabsorbed, thus creating an electron–hole pair. In the high electric field the carriers generated by recombination radiation have the same effect as the initial photogenerated carriers in the forming of the space charge domain; thereby a new avalanche domain will be nucleated. Since the new domain has the same effects of strong impact ionization and recombination radiation, new domains can be nucleated uninterruptedly by the carriers generated by the absorption of recombination radiation. The absorption length of a photon having band-gap energy in GaAs is 2 μm [23], and the corresponding absorption coefficient is $\alpha = 5 \times 10^3\,\mathrm{cm^{-1}}$. So the reabsorption time τ_α can be given as

$$\tau_\alpha \approx \left[\alpha \cdot \frac{c}{\sqrt{\varepsilon_\mathrm{r}}}\right]^{-1} \approx 2.4 \times 10^{-14}\,\mathrm{s}, \qquad (3)$$

where $c = 3 \times 10^{10}\,\mathrm{cm\,s^{-1}}$ is the velocity of photons in a vacuum and $\varepsilon_\mathrm{r} = 13.18$ is the relative dielectric constant of GaAs. The reabsorption time τ_α is commensurate with the photon transport time across the distance between two neighbouring optically activated charge domains. The nucleating time of the domain is about a picosecond order of magnitude, which is commensurate with the domain transport time before the occurrence of the impact ionization. Therefore, the number of domains in the bulk of the PCSS can be calculated to be

$$N_\mathrm{d} = \frac{l}{\tau_\mathrm{R} \cdot \upsilon_\mathrm{s} + \tau_\alpha \cdot \upsilon_\mathrm{c}} \approx 10^3, \qquad (4)$$

where $\tau_\mathrm{R} = 1$ ps is the domain nucleating time, $\upsilon_\mathrm{s} \approx 1 \times 10^7\,\mathrm{cm\,s^{-1}}$ is the velocity of the domain and $\upsilon_\mathrm{c} \approx 8 \times 10^9\,\mathrm{cm\,s^{-1}}$ is the velocity of photons in GaAs. Since the forefront optically activated charge domain crosses the switch at a speed alternating between the photon velocity and the carrier saturated drift velocity, the carrier observed velocity is greater than the carrier saturated drift velocity. In this case, the carrier observed velocity is determined to be

$$\upsilon = \frac{\tau_\mathrm{R} \cdot \upsilon_\mathrm{S} + \tau_\alpha \upsilon_\mathrm{c}}{(\tau_\mathrm{R} + \tau_\alpha)}. \qquad (5)$$

In the nonlinear mode, the carrier observed velocity predicted by (5) is about $2.0 \times 10^8\,\mathrm{cm\,s^{-1}}$, which is in good agreement with the experimental result [24].

When PCSSs operate in the nonlinear mode, the lock-on field is caused by the fixed number of space charge domains, the stable domains' electric fields and the steadfast external electric field of the domains. During the formation of the space charge domain, the large numbers of photogenerated carriers can make the electric fields of the domain increase sharply, and the impact ionization avalanche occurs immediately. Because of the impact ionization avalanche and the recombination radiation, the increase in the domain electric field is terminated immediately and fixed on the value of the intrinsic breakdown electric field. The electric field across the 'plasma region' between the domains is approximately $10^3\,\mathrm{V\,cm^{-1}}$, which is as high as the domains sustaining an electric field. Equation (4) shows that the number of domains is proportional to the length of the switch, which indicates that the lock-on voltage also increases proportionally with increase in the length of the switch; thereby the lock-on field remains constant. In our experiment, the average electric field $\bar{E}_\mathrm{d}$ of the triangular domain having a maximum electric field of 250 $\mathrm{kV\,cm^{-1}}$ is 125 $\mathrm{kV\,cm^{-1}}$; therefore, the lock-on field can be expressed as

$$E_\text{lock-on} = \frac{1}{L}\int_0^L E(x)\,\mathrm{d}x \approx E_\mathrm{s} + \frac{\bar{E}_\mathrm{d} - E_\mathrm{s}}{\tau_\mathrm{R}\upsilon_\mathrm{s} + \tau_\alpha \cdot \upsilon_\mathrm{c}} w_\mathrm{d}. \qquad (6)$$

The lock-on electric field can be calculated to be $\sim$7.1 $\mathrm{kV\,cm^{-1}}$ from (6); it shows good quantitative agreement with the experimental value.

The recovery of the lock-on effect is caused by the circuit discharges below the sustaining electric field of space charge domains. When the electric field across the switch decreases below the domain sustaining electric field which is caused by insufficient discharge energy from the circuit, the domains will be extinguished in the bulk of PCSS away from the electrodes, and then the switch enters the opening state due to the recombination of the nonequilibrium carriers.

4. Conclusion

In summary, the lock-on field of SI-GaAs PCSS has been measured under different bias voltages; the experimental observation shows that the lock-on field settles at a constant value of 6.3 kV cm^{-1} independent of the initial charge voltage, and based on the experimental data, the salient features of the lock-on effect have been explained. It is shown along the drifting direction of electrons that domains generated uninterruptedly by the reabsorption of recombination radiation from the avalanche domains are a mechanism that allow carriers to move across the device at speeds greater than their saturation velocities. The fixed number of domains, the steady-state domains electric fields and the steadfast external electric field of the domains lead to a constant value of the lock-on field. The recovery of the lock-on effect is caused by domain quenching as a result of circuit discharges below the sustaining electric field of the space charge domain.

Acknowledgments

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