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Delayed-Dipole Domain Mode of Semi-Insulating GaAs Photoconductive Semiconductor Switches*

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Abstract: A mode for the periodicity and weakening surge in semi-insulating GaAs photoconductive semiconductor switches is proposed based on the transferred-electron effect. It is shown that the periodicity and weakening surge is caused by the interaction between the self-excitation of the resonant circuit and transferred electron oscillation of the switch. The bias electric field (larger than Gunn threshold) across the switch is modulated by the AC electric field, when the instantaneous bias electric field E is swinging below Gunn electric field threshold E_T but greater than the sustaining field E_S (the minimum electric field required to support the domain) at the time of the domain reaching the anode, and then the delayed-dipole domain mode of switch is obtained. It is the photon-activated carriers that satisfy the requirement of charge domain formation on carrier concentration and device length product of $10^{12}\,cm^{-2}$, and the semi-insulating GaAs photoconductive semiconductor switch is essentially a type of photon-activated charge domain device.

Key words: semi-insulating GaAs photoconductive switch; Gunn effect; self-excitation; delayed-dipole domain mode

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1 Introduction

Photoconductive semiconductor switches (PCSSs) have potential to achieve the difficult requirement of high-voltage, high-bandwidth, long-lifetime pulse power systems. A number of semiconductors have been considered for PCSSs, but semi-insulating (SI) GaAs has been commonly chosen for fabricating devices because it switches by a nonlinear characteristic[1~5] (also known as lock-on effect or high-gain mode). This enables the devices to be triggered with low-energy light pulse from a laser diode which is both compact and inexpensive[6]. However, to date, theories to describe high gain PCSSs are incomplete or inconsistent with experimental measurements[7,8]. Considering that high gain PCSS coincides with Gunn domain device in the following: (1) Lock-on happens only in semiconductors which show transferred-electron effect or negative differential resistance (NDR); (2) The lock-on field threshold is higher than Gunn electric field threshold (the threshold of NDR); (3) The product of carrier concentration and device length (nL product) greater than $10^{12}\,cm^{-2}$ can fulfilled by optically generated carriers; so a model of luminous charge domain is proposed to explain the phenomenon of high gain PCSS[9,10].

In this paper, we analyze the periodicity and weakening surge of nonlinear PCSS based on the model of luminous charge domain, and a delayed-dipole domain mode of SI-GaAs PCSS is proposed.

2 Experiment

The PCSSs used in our experiments have a resistance of $>5\times10^7\ \Omega\cdot cm$ in total darkness. The photoconduction material used for the PCSSs is SI-GaAs with a thickness of 0.6mm, and the mobility is larger than $5500cm^2/(V\cdot s)$. The two electrodes are Au/Ge/Ni ohmic contacts, and the length of the two electrodes is 4mm. The nL product is roughly $0.6\times10^7 cm^{-2}$, which is much less than the required for forming Gunn domain.

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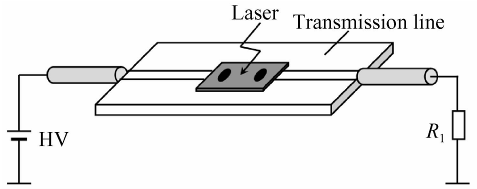

Fig.1 Schematic diagram of GaAs PCSS

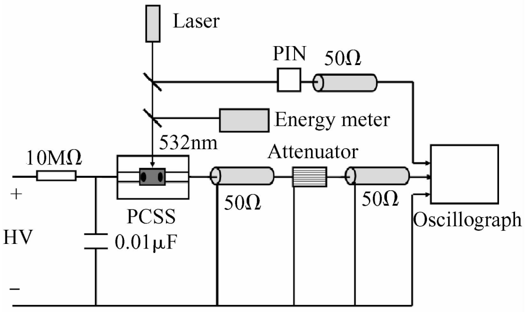

Fig.2 Testing circuit of PCSSs

The transmission line is connected from outside with two coaxial connectors as shown in Fig. 1. The Nd:YAG ns laser is used as triggers. The laser operates at a wavelength of 532nm with a pulse width of 5ns, and the laser pulse energy ranges from μJ to mJ. The storage oscilloscope used is Lecory-8500A. A 60dB coaxial attenuator with a bandwidth of 0～18GHz is used between the PCSS and the oscilloscope. Figure 2 is the basic testing circuit.

When the PCSS is triggered by laser pulse energy of 1.5mJ and the electric field across the PCSS is about 10.8kV/cm, the current waveform shown in Fig. 3 is observed. It is quite interesting that the switch output waveform exhibits a series of periodicity and weakening surge which are added on the nonlinear waveform and the duration of oscillation about 15ns.

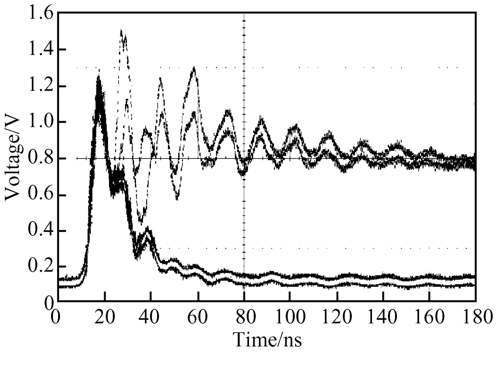

Fig.3 Superposed waveform of 10 times nonlinear periodicity and weakening surge

3 Discussion

In our experiment, the bias electric field is 10.8kV/cm, which is much higher than threshold electric field E_T (3.2～4.2kV/cm) required for NDR. Although the nL product of the PCSS is dissatisfied with the Gunn condition[11]:

$$Ln > 1 \times 10^{12}\,\mathrm{cm}^{-2} \qquad (1)$$

the photo-generated electron and hole pairs fulfill the condition of Eq. (1). In view of the fact that there are a certain number of traps of deep energy level in GaAs, such as EL_2 deep levels[12], they can generate impurity absorption. In general the impurity absorption depth is about 0.01～1cm[13,14]. In the discussion below, the maximum absorption depth is used. When the energy of the trigger laser is 1.5mJ, the laser pulse energy absorbed by the PCSS with thickness of 0.6mm is about 87.4μJ. Therefore the photo-generated carriers are calculated to be 4.6×10^{14}. The focusing laser beam has a diameter of 0.15mm. Then the concentration of photo-generated carriers is calculated to be $2.6 \times 10^{18}\,\mathrm{cm}^{-3}$. The integration along the device length is $\int_0^L n(x)\mathrm{d}x = 3.9 \times 10^{16}\,\mathrm{cm}^{-2}$, which is much bigger than $1 \times 10^{12}\,\mathrm{cm}^{-2}$. Note that the carrier's recombination time (sub-nanosecond order of magnitude[15]) is much longer than the Gunn domain growth time (picosecond order of magnitude[16]). Therefore photo-generated carriers should have the same effect with the intrinsic carriers in the forming of Gunn domain, namely photo-generated carriers supply enough carriers to form the Gunn domain. The SI-GaAs PCSS is essentially a photo-activated charge domain device (PACD) and a perfect Gunn condition should be expressed as

$$\int_0^L (n + n')\mathrm{d}L > 1 \times 10^{12}\,\mathrm{cm}^{-2} \qquad (2)$$

where n is the doping density, and n' is the photo-generated carrier density.

Based on the discussion above, the oscillation phenomenon of the output current waveform is one mode of the charge domain. Such type of behavior can partially be explained by the interaction between the transit oscillation of the PACD and the oscillation arising in the external resonant circuit as a response to the force of the transit microwave oscillation. In other words, the output waveform of PACD is generated by the bias elec-

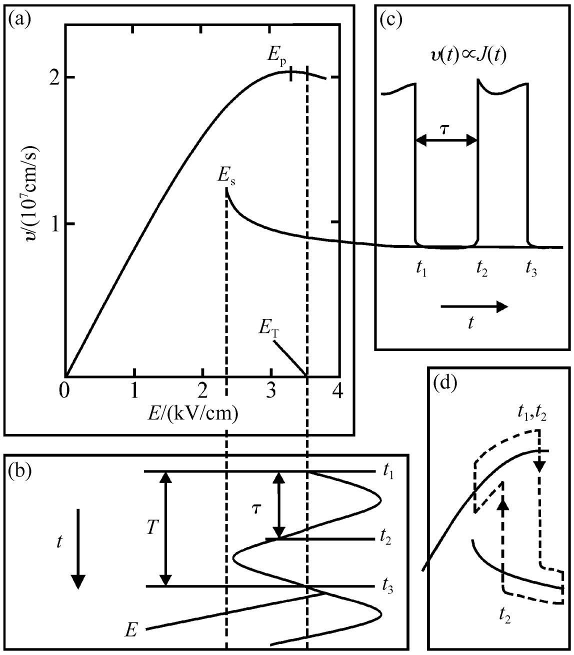

Fig. 4　Illustration of the delay domain mode　(a) Velocity-electric field characteristic of the GaAs device; (b) AC electric field waveform arisen by self-excitation of the circuit; (c) Current waveform of output; (d) Track of one cycle v-E characteristic curve

tric field and ac electric field arisen by self-excitation of the circuit.

4　Delayed-dipole domain mode

This kind of mode of trans-electron oscillator is obtained when the delay of domain is caused. Namely, if the instantaneous electric field E is such that it is greater than the sustaining field E_S but less than Gunn electric field threshold E_T when the domain reached the anode, a new domain would not be nucleated until the bias electric field rise above E_T again, and if the cycle of the resonant oscillation T is greater than the transit time τ, the nucleation of the domain is delayed, namely the delayed-dipole domain mode is obtained and the frequency of oscillation is fixed by the resonance of the external circuit[17].

Figure 4 is the schematic diagram of the delayed-dipole domain mode. Under this bias condition, the PCSS obviously worked in the nonlinear mode (lock-on effect). At the time of t_1 the E rises above the E_T, then the space charge domain began to nucleate. After the transit-time τ and at the time of t_2, the domain has reached the anode and extinguish, because the bias E become below E_T and above the E_s, the new domain cannot nucleate, and until the time of t_3, the E rises above the E_T again, and thus the new domain begin to form, namely after a cycle of self-excitation, the new domain can be nucleated. If $T > \tau > T/2$, as shown in Fig. 4, the domain nucleation will be delayed. In this case, the frequency of the domain is $1/T$, not $1/\tau$. In accordance with the experimental result in Fig. 3, the transit-time $\tau = L/v$ is about 4ns, much less than the cycle of self-excitation (about 15ns); here the velocity v of the carriers is about 10^8cm/s that is the carries velocity of lock-on effect[18]. The total oscillation time is determined by the sustaining time of lock-on effect, and the weakening of the surge is caused by the recombination of the carriers and condition of the external circuit.

5　Conclusion

In summary we have observed the delayed-dipole domain experimentally in SI-GaAs PCSS when satisfied the Gunn threshold condition. The delayed-dipole domain is caused by the interaction between the self-excitation of the resonant circuit and transferred electron oscillation of the switch. Under proper bias electric field and incidence energy, the photo-generated (or by other means) carrier have the same effect with the intrinsic carriers in the forming of Gunn domain, namely photo-generated carriers supplied enough carriers to form the Gunn domain. The semi-insulating GaAs photoconductive semiconductor switch is essentially a type of photon-activated charge domain device. The cycle of output current waveform is determined by the self-excitation of the external circuit. The weakening of the surge is caused by the recombination of the carriers and condition of the external circuit.

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半绝缘 GaAs 光电导开关的延迟偶极畴工作模式*

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摘要： 基于转移电子效应提出半绝缘光电导开关延迟偶极畴工作模式，理论分析了强场下开关的周期性减幅振荡.指出开关的周期性减幅振荡是由于外电路的自激振荡和开关的转移电子振荡共同作用引起的.开关的偏置电场在交流电场的调制下，当畴到达阳极时，开关电场下降到低于耿氏阈值电场 E_T 而高于维持电场 E_S（维持畴生存所需的最小电场），开关将工作于延迟偶极畴模式.进而从理论和实验两方面指出半绝缘 GaAs 光电导开关是一种光注入畴器件，光生载流子的产生使得载流子浓度与器件长度乘积满足产生空间电荷畴所需的条件.

关键词： 半绝缘 GaAs 光电导开关；耿效应；自激振荡；延迟偶极畴

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