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Quenched-Domain Mode of Photo-Activated Charge Domain in Semi-Insulating GaAs Devices*

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Abstract: The quenched domain mode of the photo-activated charge domain (PACD) in semi-insulating (SI) GaAs photoconductive semiconductor switches (PCSSs) is observed. We find that the quenched domain is induced by the instantaneous electric field across the PCSS being lower than the sustaining electric field of the domain during the transit of the domain. The extinction of the domain before reaching the anode can lead to a current oscillation frequency larger than the transit-time frequency when the bias electric field is lower than the threshold electric field of the nonlinear PCSS. According to the operation circuit and the physical properties of a high-field domain, an equivalent circuit of the quenched domain is presented. The equivalent circuit parameters including capacitance, resonant frequency, and inductance are calculated and measured. Our calculations agree well with the experimental results. This research provides theoretical and experimental criteria for heightening the oscillation frequency and efficiency of PACD devices.

Key words: photoconducting switch; quenched domain mode; equivalent-circuit;
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1　Introduction

Due to many advantages of operating characteristics, such as high off-state blocking voltage (over 100kV)[1], high on-state peak current (tens amperes to kiloamperes)[2,3], and fast switching (less than 1ns)[4,5], photoconductive semiconductor switches (PCSSs) are important for high-power, pulsed switching applications[6,7]. As a PCSS material, semi-insulating (SI) GaAs exhibits excellent electrical propriety, making it preferred over other photoconductive material in most pulse-power generation circuitry. Of practical importance is the ability of SI GaAs PCSSs to operate in nonlinear mode (high gain mode or lock-on effect) at high values of the applied bias. This nonlinear mode was first observed by Williamson *et al*.[8] and is highly energy efficient. Despite promising trends to date, the mechanism of the nonlinear mode is not well understood[9] and a number of unresolved problems remain. For example, during the "on" state of nonlinear PCSS, the average electric field across the PCSS is fixed on a constant value independent of the initial bias, the geometry of the PCSS, or an external trigger. The formation of current filaments within the PCSS leading to overall device failure has also been reported. Since this is highly detrimental to device reliability and overall system stability, it is necessary to understand the underlying physics for control and suppression of the internal instabilities. Several models have been proposed to explain the nonlinear mode, such as avalanche ionization[10], field-dependent trap filling[11], and double injection model[12]. In our previous research, considering that the level of the lock-on field is in a range just above the region of the Gunn effect and the photo-generated carriers can fulfill the $n \cdot l$ product criterion for forming a stable Gunn domain, a model of photo-activated charge domain (PACD) was presented[13]. One oscillation mode of PACD, namely the delayed-dipole domain has been described[14].

In this paper, another mode of PACD, namely the quenched domain mode, is proposed. Compared with the delay-dipole domain, the quenched domain mode can be as high as possible to increase the oscillation frequency and efficiency of PACD devices, and it is widely circuit tunable and suitable for local oscillator applications[15]. A detailed knowledge of the transport properties of PACD in a complex external circuit is necessary for proper circuit design. For this purpose, it is most convenient to describe the physical processes by means of an equivalent circuit. In this letter, an equivalent circuit of the PACD is given for the first time based on the physical property of the charge do-

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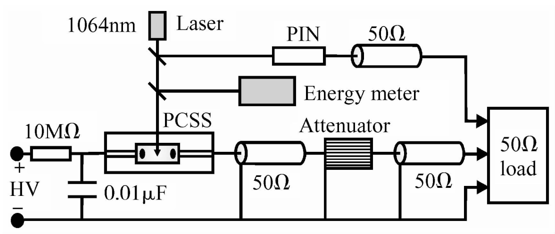

Fig.1 Schematic of testing circuit for lateral PCSS

main and characteristic of the external circuit. Moreover, due to the existence of the space charge domain in the nonlinear mode of the PCSS, the research of the equivalent circuit provides an effective method for the control of the nonlinear PCSS.

2 Experiment

The GaAs switches used in this experiment were lateral switches made from SI GaAs of high resistivity $>10^7\ \Omega \cdot cm$. The mobility was larger than $5500cm^2/(V \cdot s)$ and the carrier density was $1.5 \times 10^7 cm^{-3}$. The bulk GaAs was cut into 1.2cm bars with 0.8cm × 0.06cm cross sections. The two electrodes were fabricated from Au/Ge/Ni alloy and ohmic contacts were made with the GaAs wafer. The dimensions of the electrodes are 6mm-wide × 3mm-long and the length of the two electrodes was 4mm. The product of the electrode gap l and the intrinsic carrier density n was about $6 \times 10^6 cm^{-2}$, which is much less than the criterion ($nl > 1 \times 10^{12} cm^{-2}$) required for the nucleation of the stable domain[16]. The trigger source used was a neodymium-doped yttrium aluminum garnet nanosecond laser. The laser operated at a wavelength of 1.06μm with a pulse width of 5ns. The storage oscilloscope used was Lecory-8500A. A 60dB coaxial attenuator with a bandwidth of 0~18GHz was used between the PCSS and the oscilloscope. The testing circuit is shown in Fig. 1.

When the PCSS was triggered by the laser with the pulse energy of 0.5mJ under a bias of 2.5kV, the current wave form shown in Fig. 2 was observed. The switch output wave form exhibits a series linear periodicity and attenuation surge with a cycle of ~12 ns and maximum amplitude as high as ~1000 V. Compared to the Gunn domain, the oscillation is typically one type of transferred-electron effect.

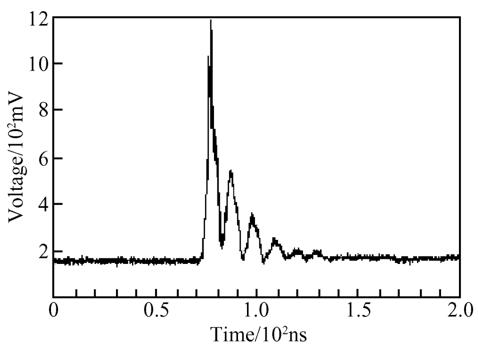

Fig.2 Oscillation current wave form of the PCSS

3 Equivalent-circuit

Due to the same effect as the intrinsic carriers in forming the space charge domain[17], the carriers generated by laser pulse are a dominating mechanism for formation of the domain in case of intrinsic carrier shortage. For SI-GaAs with the absorption depth of 1mm, the energy of the trigger optical pulse with energy of 0.5mJ absorbed by the PCSS is about 226μJ. Therefore, the photo-generated carries must fulfill the criterion required for the nucleation of the stable domain. Since the bias field of 6.25kV/cm is higher than the Gunn threshold electric field (~ 4kV/cm), the Gunn domain must be nucleated in the bulk of the device.

Figure 3 shows that the cycle of current oscillation is about 12 ns, which is much shorter than the time τ for the domain moving at the saturated drift velocity υ_s (about 1×10^7 cm/s) to cross the switch ($\tau = l/\upsilon_s = 40ns$). So this oscillation is not the transit-time oscillation of the Gunn domain. Such type of behavior can partially be explained by the interaction of the transit oscillation of the domain and the oscillation excited in the external resonant circuit as a response to the force of the transit microwave oscillation. Namely, the bias electric field (larger than the Gunn threshold electric field E_T) is modulated by the AC electric field in the external resonant circuit, when the instantaneous electric field E across the switch swings below the sustaining electric field E_s (the minimum electric field required to support the domain), the domain will be extinguished somewhere away from the anode. The premature extinction of the domain can lead to an oscillation cycle T less than the τ.

The equivalent circuits of the external resonant circuit, the domain, and the device outside the domain are shown in Fig. 3. The symbols in Fig. 3 have the following significance: R_0 and C_0 correspond to the "on" resistance and the capacitance of the device outside the domain, respectively, R_d and C_d denote the resistance and the capacitance of high electric field domain, respectively, R_L is the resistance of the load which has the fixed value of 50Ω, L is the total inductance of the circuit and the typical value of L is 1 nH, which can be obtained experimentally, and C_e is the capacitance of an external circuit which has a quantity of 0.01μF. Due to the carrier density within the domain being much greater than the carrier densi-

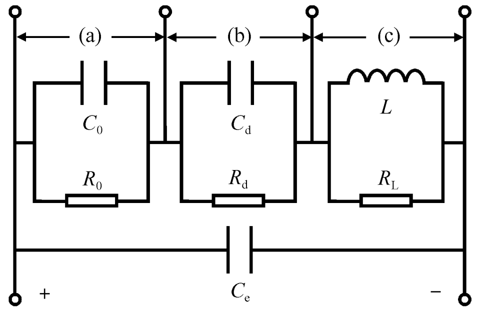

Fig. 3 Equivalent circuit of the oscillation mode of PCSS (a) Bulk equivalent circuit of PCSS; (b) Domain equivalent circuit; (c) Inductance and load lumped circuit

ty outside the domain, the total resistance of the PCSS is approximately equal to R_0, and it can be given as

$$R_0 = \frac{l^2 h\nu}{E_a q\mu} \tag{1}$$

where $h\nu$ is the photon energy, E_a is the total energy absorbed from the optical pulse, q is the unit of electric charge, and μ is the mobility ($\mu_n + \mu_p$). Based on the experiment data used above, R_0 can be calculated to be approximately 0.2Ω. The capacitance of the Gunn domain can be expressed as

$$C_d = \frac{\varepsilon A}{w_d} \tag{2}$$

in which A is the device area, ε is the dielectric constant of GaAs, and w_d is the domain width. Since the length of the device is much larger than the domain width w_d, $C_0 \ll C_d$, the device used in our experiment has an area of $0.8\text{cm} \times 0.06\text{cm}$, $\varepsilon = 1.17 \times 10^{-10}\ \text{C}^2/(\text{N} \cdot \text{m}^2)$, and a logical value for domain width w_d is $1\mu\text{m}$, so we obtain $C_d = 53$ pF. Compared with C_e, the influence on the output characteristic of the device caused by C_d is negligible, and the AC current $I(t)$ through the load R_L can be given by

$$I(t) = I_0 e^{-\alpha t} \sin\omega t \tag{3}$$

where

$$\alpha = (R_L R_0 C_e + L)/[2LC_e(R_L + R_0)] \tag{4}$$

$$\omega = \sqrt{R_L/[LC_e(R_L + R_0)] - \alpha^2} \tag{5}$$

From Eqs. (1) ~ (5), the cycle of oscillation caused by the resonant circuit is calculated to be $T = 2\pi/\omega = 20$ns, which is very close to the cycle of oscillation (~12ns) observed experimentally (see Fig. 3).

4 Extinction of the domain

Figure 4 shows the schematic diagram of the extinction of the charge domain. From Figs. 4 (a) and (b), at time t_1, E rises above E_T, electrons scatter into the satellite L valley, and then the space charge domain begins to nucleate. At the time t_2 (before the domain formed has reached the anode), E drops below E_s, whereupon the domain will be extinguished. At time t_3, E rises above E_T and a new domain will be formed. Accordingly, the output current generates the periodical oscillation. The dashed line shown in Fig. 4 (b) is the track of one cycle of the υ-E characteristic curve. The frequency of oscillation is fixed by the resonance of the external circuit, as loaded by the admittance of the PCSS, and is less or much greater than the transit-time frequency. The requirement that the domain be extinguished before reaching the anode means that the transit time cannot be much less than a half cycle of the AC electric field of the resonator.

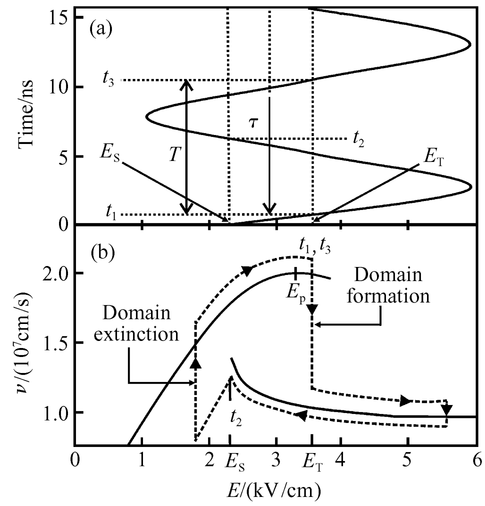

Fig. 4 Schematic of domain extinction (a) AC electric field exited in external circuit; (b) Solid curve corresponds to characteristic curve of drift velocity υ versus electric field E for GaAs devices and the dashed line to one cycle of domain extinction

5 Conclusion

In summary, the quenched domain mode of PACD in SI-GaAs PCSSs has been observed. Based on the properties of a charge domain and resonant characteristic of the external circuit, the equivalent circuit for the current oscillations of SI-GaAs PCSS has been presented. We show that the current oscillation frequency larger than the transit-time frequency is attributed to the extinction of the domain before the domain reaches the anode. The calculations agree well with the experimental result. The observation of the quenched domain mode provides theoretical and experimental criteria for increasing the oscillation frequency and efficiency of PACD devices. Furthermore, the extinction of the domain by self-oscillation of an external resonant circuit provides a method for the control of the lock-on effect of nonlinear PCSSs, which requires further study for nonlinear PCSSs.

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半绝缘 GaAs 光电导开关中光激发电荷畴的猝灭畴模式*

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摘要： 在半绝缘 GaAs 光电导开关中发现了光激发电荷畴的猝灭畴模式．分析指出畴猝灭是由于畴在渡越中开关的瞬时电场低于畴的维持电场引起的，并指出在开关电场低于非线性光电导开关阈值电场条件下，在到达阳极前畴的猝灭可导致开关输出电流的振荡频率高于畴的渡越时间频率．根据开关工作电路条件及畴特性给出了猝灭畴模式的等效电路，计算了相应的电路参数，计算结果与实验基本吻合．该研究为提高光注入畴器件的振荡频率及工作效率提供了理论和实验依据．

关键词： 光电导开关；猝灭畴模式；等效电路

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