

Optically Activated Charge Domain Model for High-Gain GaAs Photoconductive Switches^{*}

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Abstract: A model for theoretical analysis of nonlinear (or high gain) mode of photoconductive semiconductor switches (PCSS's) is proposed. The switching transition of high-gain PCSS's can be described with an optically activated charge domain. The switching characteristics including rise time, delay and their relationship to electric field strength, optical trigger energies are discussed. The formation and radiation transit, accumulation of the charge domain are related with the triggering and sustaining phases of PCSS's, respectively. The results of the mathematical model on this mechanism agree with experimental results.

Key words: photoconductive switches; high gain mode; optically activated charge domain

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1 Introduction

Photoconductive semiconductor switches (PCSS's) have gained increasing interest recently as the most promising devices in ultra-high speed electronics and pulsed power systems. The primary characteristics of PCSS's are their jitter-free, low inductance and high-speed response to laser pulse. A number of experimental investigations have been performed to characterize the electrical and optical properties of high-gain PCSS's^[1-5]. It is indicated that nonlinear mode can be divided into three phases: triggering (transition process), sustaining (lock-on or steady-state) and recovery. To explain all these phenomena, some theoretical studies have dealt with the nonlinear process^[6]. The concentration of research has been put on the transition behavior of high-gain PCSS's^[7,8]. Even though several mechanisms have been considered, there is still

lack of a unified physical picture of nonlinear switching transition.

In this paper, we attempt to develop an optically activated charge domain mechanism for qualitative explanation of transition process in PCSS's nonlinear mode and to discuss the switching characteristics including rise time, delay and their relationship to electric field strength, optical trigger energies. This theory describes time evolution of transition switching as formation, transit and accumulation of an optically activated and avalanche luminous charge domain.

2 Experiments

The PCSS's used in our experiments have a resistivity of $> 5 \times 10^7 \Omega \cdot \text{cm}$ in total darkness. A Nd:YAG frequency-doubled laser was used as trigger. The laser operated at a wavelength of 532nm with a pulse width of 200ps, and the laser pulse en-

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ergy ranges from μJ to mJ . It is well known that there is a threshold condition for PCSS to work in the lock-on region. The lock-on threshold condition consists of a minimum electric field and a minimum triggering laser energy at this electric field, as is shown in Fig. 1 by plotting the laser trigger energy versus the electric bias field. The circle dots are experimental data. The threshold condition is along the line, which separates the lock-on region (region 1) from the linear region (region 2). The requirement on the triggering laser energy is essential to meet the requirement of Gunn-domain formation by generating enough carriers. The requirement on the electric field threshold is borne on the requirement of NDR (negative differential resistance) threshold (Gunn threshold), which ranges from 3.2 kV/cm to 4 kV/cm for GaAs. In our experiments, the electric field threshold of high-gain mode is from 4.1 kV/cm to 11 kV/cm , which are higher than NDR threshold of GaAs.

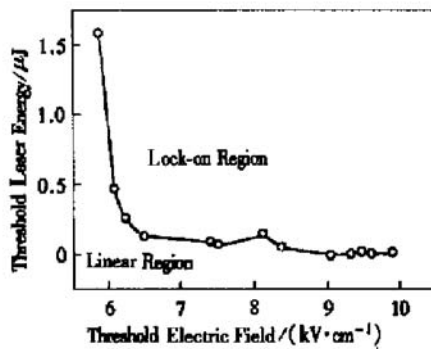


FIG. 1 Lock-on Threshold Condition

At the threshold conditions, the current waveforms shown in Fig. 2(a) and (b) were observed. These two figures correspond to two different threshold conditions: (electric field, trigger energy) equal to $(9.0\text{ kV/cm}, 33\mu\text{J})$ and $(11.0\text{ kV/cm}, 21\mu\text{J})$ respectively. The waveforms of repeated pulses can be clearly observed after the laser triggering. The intervals between two adjacent pulses keep unchanged and they are approximately 6.5 ns . The temporary current oscillation disappears gradually as large current density formed in the switch (PCSS turns into lock-on). As can be seen from

Fig. 2(a) and (b), with the falling edges of the current pulses rising continuously, conducting electron-hole plasma channels are gradually formed after several pulses (domains)^[4]. The switch runs into high-gain mode. Such kinds of pulsed current waveform can not be found at the lock-on region and the linear region in Fig. 1, where the (electric field, trigger laser energy) pairs are away from the threshold condition. The oscillation current waveforms observed in Fig. 2(a) and (b) are a clear indication of repeated charge domain formed in PCSS.

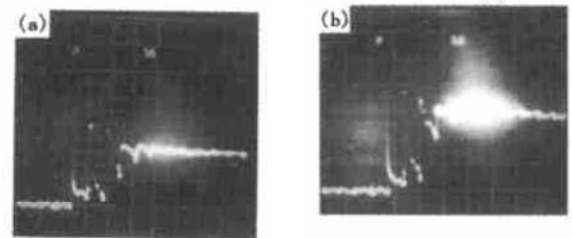


FIG. 2 Current Waveforms Under Different Electric Fields, Trigger Laser Energy Threshold Value (a) $Y/\text{div } 1\text{ V}, X/\text{div } 5\text{ ns}$; (b) $Y/\text{div } 1\text{ V}, X/\text{div } 5\text{ ns}$

3 Description of Model

The lateral SI-GaAs switch and the coordinate used in this analysis are shown in Fig. 3. The pulsed laser is incident on the active area (the gap between cathode and anode). The bias field and current of the switch are in the z direction. For SI-GaAs, E_{sb} denotes the avalanche breakdown field,

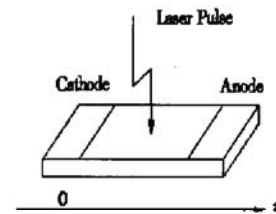


FIG. 3 Diagram of Switch and Associated Coordinator System

and E_{gt} , the Gunn threshold (or NDR) field. The initial bias voltage V_i satisfies $E_{gt} < E_i < E_{sb}$. It is assumed that SI-GaAs used is uniformity in electrical

properties and few charge carriers exist in it. Thus, no electrical response occurs, although it is biased in NDR region.

When a laser pulse is focused into a small spot, a number of photo-generated electron-hole pairs are introduced to initial electrical state. The photo-generated electrons will move to the anode and holes to the cathode under the biased field. Since the field E_i is in a range just above the range of the Gunn effect, Gunn domain is created which causes large enough localized field enhancements. The domain field E_d is assumed to be so high that the combined field $E_d + E_i$ reaches or is equal to E_{sb} . Then, localized avalanche phenomenon will occur in the vicinity of light incident spot. Localized avalanche means the appearance of strong impact ionization or carrier amplification in domain region. In addition, this region generally becomes a strong light radiation source. Some of the recombination has produced immediately, before the domain selves is absorbed to produce new domain in the high field again. The generation of carries ahead of the space charge zone enables the ionizing surface to propagate faster than either electron or hole drift velocities.

From Poisson's Equation, notice that the carrier recombination time (in ns) is much longer than the domain growth time (in ns), the optically injected carriers should participate the whole process of domain growth, we have

$$\frac{\partial \rho}{\partial t} + \frac{\partial I}{\partial z} = 0 \quad (1)$$

$$J = \sigma E = en\mu E = env \quad (2)$$

$$n = n_0 + n' \quad (3)$$

$$\frac{\partial}{\partial t}(en'') + \frac{\partial}{\partial z}(en''v) = 0 \quad (4)$$

$$\frac{\partial E}{\partial z} = \frac{e}{\epsilon}(n'' - n) \quad (5)$$

where n_0 is the dark carrier concentration of SI-GaAs, n' is photo-generated carrier concentration, n'' expresses carrier concentration irregular distribution caused by initial incident pulse laser.

Substituting Eq. (5) to Eq. (4), in the time of

the domain growth $\partial n/\partial t = 0$,

$$\epsilon \frac{\partial E}{\partial t} + e \left[\frac{\epsilon}{e} \times \frac{\partial E}{\partial z} + n \right] v = J_t(t) \quad (6)$$

$J_t(t)$ is the density of total current, $J = e \left[\frac{\epsilon}{e} \times \frac{\partial E}{\partial z} + n \right] v$ is the density of drift current.

The domain moves at constant velocity v_d , when the domain growths up to stable, the field inside the domain becomes stable distribution

$$E(z^*) = E(z - v_d t) \quad (7)$$

while

$$\frac{\partial E}{\partial t} = -v_d \frac{dE}{dz^*}, \quad \frac{\partial E}{\partial z} = \frac{dE}{dz^*} \quad (8)$$

Substituting Eq. (8) to Eq. (6), we obtained

$$-env_d \frac{dE}{dz^*} + e \left[\frac{\epsilon}{e} \times \frac{dE}{dz^*} + n \right] v = J_t \quad (9)$$

$$\epsilon(v - v_d) \frac{dE}{dz^*} = J_t - env \quad (10)$$

The field outside the domain is of constant E_0 , so

$$J_t = env_o, \quad v_o = v(E_o) \quad (11)$$

$$\epsilon(v - v_d) \frac{dE}{dz^*} = env_o - env = -en(v - v_o) \quad (12)$$

Average drift velocity (v_d) of the electrons inside the domain is equal to the drift velocity (v_o) of the electrons outside the domain, $v_d = v_o$

$$(v_o - v) \left[\frac{dE}{dz^*} + \frac{en}{\epsilon} \right] = 0 \quad (13)$$

$$\frac{dE}{dz^*} = -\frac{en}{\epsilon} \quad (14)$$

Equation (14) described a triangle domain, showed in Fig. 4

$$\tan \alpha = \tan \left[\frac{\pi}{2} - \beta \right] = \cot \beta = \frac{E_2 - E_1}{b} = \frac{en}{\epsilon} \quad (15)$$

So we obtained the domain width as follows

$$b = \frac{\epsilon}{en}(E_2 - E_1) \quad (16)$$

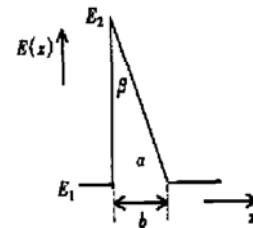


FIG. 4 Field Distribution of Growing Domain
Field(Triangle Domain)

When impact ionization occurs in domain region, avalanche carriers can be described as

$$n_b(t) = n \exp(\alpha v t), \quad \alpha = A \exp(-B/E) \quad (17)$$

where α is coefficient of impact ionization, v is electron velocity, A and B are constant.

Take effective coefficient of impact ionization α_{eff} to express α , and n_c expresses critical carrier concentration corresponding the avalanche impact ionization, we have

$$\alpha_{\text{eff}} = 1.8 \times 10^{-35} E^7 (1/\text{cm}) \quad (18)$$

$$n \exp(\alpha_{\text{eff}} z_c) = n_c \quad (19)$$

where $z_c = v_c t$. Since the n is proportional to the incident pulse laser, $\alpha_{\text{eff}} \propto E$, so the triggering depends on the electrical and optical thresholds that are inversely related.

From the ratio R_c of photon radiation in semiconductor^[9]

$$R_c = [(\Delta n/n_0)^2 + 1] R \quad (20)$$

where $\Delta n = \Delta p = n_b - n_0$, R is the recombination ratio at equilibrium. It is indicated that recombination radiation becomes strongly as the deepening of the impact ionization. This is a mechanics picture of optically activated charge domain that enable the displacement of ionization region becomes faster. So, the time of total ionization between electrodes when triggering GaAs PCSS's can be described as

$$t_d = \frac{z}{v_d} + \frac{L - z}{v_s} \quad (21)$$

where L is a gap length between the electrodes, v_s is the velocity of light in GaAs. The first item is the time that carriers move at saturated velocity and the second item is the time of electroluminescence propagation. Equation (21) is also the time for carriers across a gap of switches' electrodes.

In GaAs, $v_s = 7.5 \times 10^9 \text{ cm/s}$, if

$$\frac{z}{L - z} = \frac{b}{h} \quad (22)$$

where h is absorb depth of GaAs and taking $L = 3 \text{ mm}$, $v_d = 10^7 \text{ cm/s}$, $b = 0.1 \mu\text{m}$, $h = 1 \mu\text{m}$ to estimate, we obtained $t_d \approx 2.77 \text{ ns}$; so, the average velocity for carriers across the gap can be described as

$$\bar{v} = \frac{L}{t_d} = 1.08 \times 10^8 \text{ cm/s}$$

Because of photo-ionization, the large electric field associated with the luminous charge domain allows virtual propagation of the carriers avalanche ionization at speeds above 10^8 cm/s , well in excess of the carrier saturated drift velocity, which is identical with the observed results from experiment^[1,5].

The delay time of GaAs PCSS's t_c means that from pulse laser incidence to strong impact ionization occurs in domain and can be denoted as

$$t_c = \frac{\ln n_c - \ln n}{v_d \alpha_{\text{eff}}} \quad (23)$$

At critical state, take $n = 10^{17} / \text{cm}^3$, $n_c = 10^{24} / \text{cm}^3$, $v_d = 10^7 \text{ cm/s}$, then $t_c = 1.48 \text{ ns}$. The electric pulse rise time can be given as

$$t_r = t_d - t_c = 1.29 \text{ ns}$$

Both t_c and t_r are conform to observed results^[5].

4 Conclusion

In conclusion, we suggest that the high gain mode of GaAs PCSS's have a relation to the growth and recombination radiation of optically activated charge domain. The physical mechanism can be described as follows: at sufficient bias electric field, incident pulse laser generates electron hole pairs and enables Gunn domain to grow. Under electrical and optical thresholds' conditions, Gunn domain might create large enough field enhancements to produce avalanche carrier generation. Recombination radiation inside the domain becomes the new light source, the switch stays on after the trigger pulse is over. Self-absorption ahead of the domain zone enables the ionizing surface to propagate faster than the carrier saturated drift velocity, the switch turn-on. Maintenance field of domain depends on the lock-on field; the switch resistance returns when the field drops below the lock-on field. The results of the mathematical model on this mechanism agree with experimental results.

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高倍增 GaAs 光电导开关的光激发电荷畴模型*

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摘要: 结合实验中观察到的光激发电荷畴现象, 提出光激发电荷畴理论模型描述高倍增 GaAs 光电导开关的瞬态特性, 讨论了高倍增 GaAs 光电导开关的非线性特性如上升时间、时间延迟和光能、电场阈值, 光激发电荷畴的成核、生长以及畴内发生的碰撞电离和辐射复合决定了高倍增 GaAs 光电导开关的引发和维持相, 理论计算结果与实验测试相符合。

关键词: 光电导开关; 高倍增模式; 光激发电荷畴

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