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# Investigation of GaAs Photoconductive Switch Irradiated by 1553nm Laser Pulse*

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**Abstract:** Gallium arsenide (GaAs) photoconductive semiconductor switches (PCSS' s) with a 1.55mm gap spacing trigged by 1553nm femtosecond fiber laser pulse is presented. The switches are biased with 3.33~ 10.3kV/ cm and irradiated by femtosecond fiber laser operated at a wavelength of 1553nm with pulse width of 200fs and pulse energy of 0.2nJ. The experiments show that, even if the semi-insulating GaAs photoconductive switch operates under the electrical field of 10.3kV/ cm, it will be still linear response, and a clear corresponding output electric pulse with the peak voltage of 0.8mV is captured. From the weak photoconductivity on laser intensity, photoabsorption mediated by EL2 deep level defects is suggested, as the primary process for the photoconductivity.

**Key words:** semi-insulating GaAs; photoconductive switch; EL2 deep level

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## 1 Introduction

Photoconductive (PC) switches have unique properties over conventional high power switches. These include low trigger jitter, high-speed response to laser pulse, picosecond rise time, GHz repetition rate, low inductance and capacitance, optical isolation of the trigger[1~3]. The high power and ultra-fast and high-voltage switches using photoconductive switches trigged by ultrashort pulse lasers can be used in a large number of applications ranging from high-speed detectors for communication and modulators and fast, high voltage pulse generation, and time-domain measure, to high power microware generation. Photoconductive switches as power generations have very wide applications to radar, communications, due to their properties which are resisting high voltage, high power, and ultra-wide-band.

GaAs used as the ultrafast PC material has a distinct advantage of the high dark resistivity ($10^7$ ~ $10^8 \Omega \cdot$ cm)[4]. This is very important for applications of PC switches. For example, the efficiency of a PC power generation increases with the bias electric field and is limited by the breakdown field of the PC power generation. For PC detector, the noise in signal current of a PC power generation is inversely proportional to the dark resistivity. The

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optical band gap of GaAs is 1.43eV at room temperature, corresponding to a wavelength of 876nm and GaAs as a photoconductive switch material can absorb light strongly with absorption coefficient in the range of $10^5 cm^{-1}$ under 876nm. So, semi-insulating GaAs photoconductive switches trigged by 532, 780, 876, and 1064nm laser pulse were often reported[5~7]. Almost no one reports the photoconductivity of the switch trigged by 1553nm laser pulse.

In this paper, we report the results of a lateral GaAs photoconductive switch with a 1.55mm gap spacing trigged by 1553nm optical pulse. It is found that the switch operates in a linear mode at 1553nm. It is impossibly intrinsic absorption mechanism for this photoconductivity, and the photoabsorption mediated by EL2 in band gap contribute to the photoconductivity.

## 2 Experiment

The experimental setup is shown in Fig. 1. The switch sample consists of a 0.6mm thick piece of semi-insulating GaAs with a dark resistivity over $5 \times 10^7 \Omega \cdot cm$ and a mobility over $5500 cm^2/(V \cdot s)$. The sample measured is 4mm × 6mm. Au-Ni-Ge contacts with a thickness of 900nm are placed on the substrate of copper board with a transmission line which is connected to the outside by two coaxial connectors. Insulation protection of the switch, which is different from the high resistivity water or high pressure $SF_6$, has adopted multilayer transparent dielectical materials coated on the surface of the GaAs wafer shown in Fig. 2. The first layer is thick $Si_3N_4$ film and the second layer is a new type of solid-state surface protection material called organopolysiloxane gel. The contacts are separated by a 1.55mm gap. When the spacial gap of GaAs is illuminated, the optical output of a laser controls the current of the switch. A laser (wavelength= 1553nm, photon energy= 0.8eV) with a pulse energy of approximately 0.2nJ and a pulse duration of 200fs and a laser power of 4.38mW is used to activate the switch. All signals are recorded by Tektronix TDS3032, and pulse energy is monitored by a KSDP2210-CAS-1 optical energy detector. The sample is pulse biased up to voltages from 0.5kV to 1.55kV, and corresponding to an applied field from 3.33kV/cm to 10.3kV/cm. The electrical pulse of the switch has a weak change at 1553nm. Figure 3 shows the electrical output of the switch when it is biased with 1.0 ~ 1.55kV. The average peak voltage is 0.8mV corresponding to peak current of 16μA. The three transparent dielectric films as insulating protection have a transmittance of 92%, and the GaAs PCSS has a luminous flux of 3.4mW and a quanta efficiency of 0.00376.

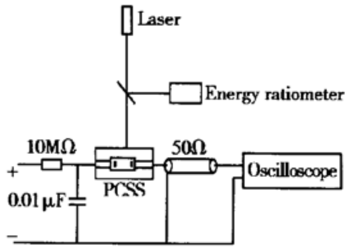

Fig. 1 Experimental setup of GaAs PCSS's

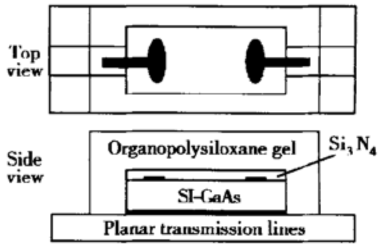

Fig. 2 Insulating structure of the switch

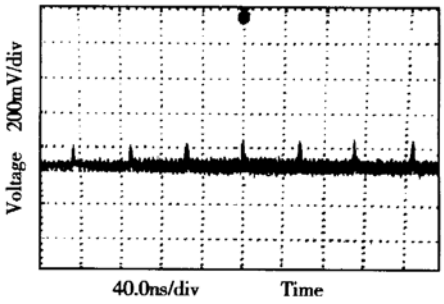

Fig. 3 Electrical output of the switch Bias voltage is 1550V.

## 3 Discussion

When the switch is trigged by a wavelength over 876nm, there are several possibilities for the photoconductivity in GaAs: (1) the absorption edge of semiconductors is shifted under the influence of electric fields (Franz-Keldysh effect), (2) the two-photon absorption, (3) exciton absorption, and (4) intrinsic deep-level defects absorption.

Franz-Keldysh effect of electric fields on the optical absorption at the band edge can be described as photon assisted tunneling through the energy barrier of the band gap. Under high-intensity of electric field, the absorption edge of semiconductor is shifted to lower photon energies or to longer wavelengths. The change in wavelength $\Delta\lambda$ dependent function for the bias field $E$ is given by[8]:

$$\frac{1}{\hbar}\left[(qE)^2\frac{\hbar^2}{m_r}\right]^{\frac{1}{3}} = \frac{2\pi c}{\lambda_1\lambda_2}\Delta\lambda \tag{1}$$

where $q$ is the unit electron charge, $m_r$ is the effective mass of the electron, $\hbar$ is Planck's constant, $c$ is the velocity of light in vacuum, $\lambda_1$ and $\lambda_2$ are absorption wavelengths. If the absorption wavelength is changed from 876nm to 1553nm, the biased field should be over $10^5$kV/cm. But in our experiment, the maximum field is 10.3kV/cm. It suggests that the photoconductivity of the sample at 1553nm can not be the origin of Franz-Keldysh effect.

Although the photon energy of 1553nm as trigging pulse light is greater than one-half the band gap of GaAs, the excitation power (4.38mW) is too low for two-photon absorption. From Reference[9], if the photocurrent comes from two-photon absorption, the intensity of the laser power should be 200MW/cm$^2$. This suggests that the primary mechanism of photoconductivity is not the two-photon absorption at a level of 4.38mW excitation power.

Exciton band is near the conduction band in the band gap. In the material of a direct-gap semiconductor, the electrons of the valence band absorbing the photon energy $\hbar\upsilon \geqslant E_g - E_x$ can not be excited to conduction band and form the excited electron-hole (exciton) because of the Coulomb electron-hole interaction, where $E_x$ is the exciton binding energy. The foundational exciton binding energy of GaAs is 4meV[8]. If exciton is formed, the minimum exciting photon energy should be 1.426eV. It suggests that there are not excitons in the photoconductive switch trigged by 1553nm (photon energy ≈ 0.8eV).

In the undoped semi-insulating GaAs, EL2 is a deep level of intrinsic defect due to excess arsenic. The EL2 locates at 0.8eV (~ 1553nm) above valence band[10]. The EL2 in the band gap acts as a step, and the absorption process can be assumed as two steps by 1553nm laser excitation: an electron of valence band absorbs photon energy and is excited to the EL2, and the electron in the EL2 absorbs photon energy and is excited to upper conduction band. Meanwhile, the EL2 is also a deep-level recombining center, and the recombination of electron-hole can be also assumed as two steps: firstly, an electron falls from conduction band to the EL2; secondly, the electron falls from the EL2 to valence band and recombines with a hole. Figure 4 shows the micro processes of absorption and recombination of photocurrents. A: Electrons of valence band are excited to unoccupied EL2, or holes are excited from unoccupied EL2 to valence band. B: Electrons are excited from occupied EL2 to upper conduction band. C: Electrons fall from upper conduction band to lower conduction band. D: Electrons are captured from lower conduction band to unoccupied EL2. E: Electrons fall from occupied EL2 to valence band and recombines with holes in valence band, or holes are captured from valence band to occupied EL2.

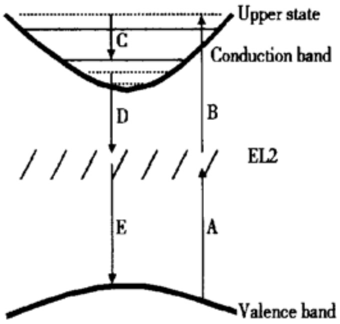

Fig. 4 Excitation and recombination processes of photo-carriers

The phenomenon of photoconduction shows that the photocurrents production process is faster than the electron-hole recombination process. We neglect the electron-hole recombination and develop a rate-equation model for the excitation and recombination of electrons:

$$\frac{dN_c}{dt} = \frac{\alpha_1 I}{\hbar\upsilon}f_t - \frac{N_c}{\tau_1} \tag{2}$$

$$\frac{dn_c}{dt} = \frac{N_c}{\tau_1} - \gamma_t n_c(1 - f_t) \tag{3}$$

$$\frac{dn_t}{dt} = \frac{\alpha_2 I}{\hbar\upsilon}(1 - f_t) + \gamma_t n_c(1 - f_t) - \frac{n_t}{\tau_2} - \frac{\alpha_1 I}{\hbar\upsilon}f_t \tag{4}$$

where $N_c$ is the density of the upper conduction band, $n_c$

is the density of the lower conduction band, $n_t$ is the density of the occupied EL2 by electrons, $\alpha_1$ is unsaturated absorption coefficients between the EL2 and upper conduction band, $\alpha_2$ is unsaturated absorption coefficients between the EL2 and valence band, $I(\upsilon)$ is the incident light intensity, $\tau_1$ is the decay time of electrons from upper conduction band to lower conduction band, $\gamma_t$ is the captured rate of electrons from lower conduction band to the EL2, $\tau_2$ is the decay time of electrons from the EL2 to valence band, $f_t = n_t / N_t$ is the fraction of the occupied EL2 by electrons, and $N_t$ is the density of the EL2. When the system is to be a steady state, there are approximately $\mathrm{d}N_c/\mathrm{d}t = \mathrm{d}n_c/\mathrm{d}t = \mathrm{d}n_t/\mathrm{d}t = 0$. The electrons density is obtained as follows:

$$N_c = \frac{\alpha_1 \alpha_2 \tau_1 \tau_2 I^2}{(N_t \hbar\upsilon + \alpha_2 \tau_2 I)\hbar\upsilon} = \frac{\alpha_1 \tau_1 N_t (I/I_0)^2}{(1 + I/I_0)\alpha_2 \tau_2} \quad (5)$$

$$n_c = \frac{\alpha_1 \alpha_2 \tau_2 I^2}{\hbar^2 \upsilon^2 \gamma_t N_t} = \frac{\alpha_1 N_t (I/I_0)^2}{\alpha_2 \tau_2 \gamma_t} \quad (6)$$

$$n_t = \frac{\alpha_1 \alpha_2 \tau_2}{(N_t \hbar\upsilon + \alpha_2 \tau_2 I)} = \frac{N_t (I/I_0)}{(1 + I/I_0)} \quad (7)$$

where $I_0 = \hbar\upsilon N_t / \alpha_2 \tau_2$ is a unit of laser light intensity, $I/I_0$ is a normalized laser light intensity without unit. The net electrons density of conduction band is as follows:

$$N_{net} = N_c + n_c = \frac{\alpha_1 \tau_1 N_t (I/I_0)^2}{(1 + I/I_0)\alpha_2 \tau_2} + \frac{N_t (I/I_0)}{(1 + I/I_0)} \quad (8)$$

From Eq. (8), we can deduce that the density of EL2 is more, the density of net electron in conduction band is more. These suggest that photoabsorption mediated by the EL2 in semi-insulating GaAs PCSS plays an important role for the photoconductivity at 1553nm and a low pulse energy.

## 4 Conclusion

In summary, we demonstrate experiments on a semi-insulating GaAs PCSS with a 1.55mm gap spacing trigged by 1553nm laser pulses. Although the bias field is 10.3kV/cm on the GaAs PCSS, the output voltage pulse is weak because the wavelength of the trigging light is longer than the limit of optical wavelength of GaAs and the trigging pulse energy is too low. And photoabsorption mediated by the EL2 in semi-insulating GaAs PCSS is responsible for the photoconductivity.

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# 用 1553nm 激光脉冲触发 GaAs 光电导开关的研究[*]

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**摘要**: 用 1553nm 飞秒光纤激光器触发半绝缘 GaAs 光电导开关的实验表明, 当光电导开关处于 3.33～10.3kV/cm 的直流偏置电场并被脉冲宽度 200fs 且单脉冲能量 0.2nJ 的激光脉冲照射时, 开关表现为线性工作模式, 开关输出峰值电压为 0.8mV. 分析表明, 开关对波长为 1553nm 触发激光脉冲表现出的弱光电导现象起因于半绝缘 GaAs 材料 EL2 深能级的作用.

**关键词**: 半绝缘 GaAs; 光电导开关; EL2 深能级

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