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Peculiar Photoconduction in Semi-Insulating GaAs Photoconductive Switch Triggered by 1064nm Laser Pulse*

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Abstract: The peculiar photoconduction in semi-insulating GaAs photoconductive switch being triggered by 1064nm laser pulse is reported. The gap between two electrodes of the switch is 4mm. When it is triggered by laser pulse with energy of 0.8mJ and the pulse width of 5ns, and operated at biased electric field of 2.0 and 6.0kV/cm, both linear and nonlinear modes of the switch are observed respectively. Whereas the biased electric field adds to 9.5kV/cm, and the triggered laser is in range of 0.5～1.0mJ, the peculiar performed characteristic is observed: the switch gives a linear waveform firstly, and then after a delay-time of about 20～250ns, it outputs a nonlinear waveform again. The physical mechanism of this specific phenomenon is associated with the anti-site-defects of semi-insulating GaAs and two-step-single-photon absorption. The delay time between linear waveform and nonlinear waveform is calculated, and the result matches the experiments.

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

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1 Introduction

High power ultra-short electrical pulse is important for the application of ultra-wide-band (UWB) radar and ultra-wide-band communication[1～3]. For generating an electrical pulse at ultra-short width compatible with high power, the photoconductive semiconductor switches (PCSSs) are more effective. When semi-insulating GaAs photoconductive switches (SI-GaAs PCSSs) are biased at low electric fields and triggered by ultra-short laser pulse, the SI-GaAs PCSSs can operate in the linear mode. Whereas the biased field is above 5.6kV/cm, the SI-GaAs PCSS is capable of switching in a nonlinear mode (also known as lock-on effect or high-gain mode). The pulse waveform of the linear mode is very different from that of the nonlinear mode. Within the last decade, the linear mode and nonlinear mode have been reported in many papers[4～8]. In this paper, we would like to show our experiment observation of a peculiar photoconduction when the SI-GaAs PCSS is triggered by the laser pulse of 1064nm. Besides the current pulse waveform of linear and nonlinear, we also observed a peculiar phenomenon, which shows the switch enters the linear mode firstly, after a delay-time of about 20～250ns, the triggering laser pulse has gone out, the switch undergoes nonlinear mode. The mechanism and characteristic of this peculiar phenomenon are analyzed by using GaAs EL2 energy level.

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2 Experiment

In optically controlled semiconductor switch, the photo-generated electron-hole pairs determined the current pulse. The photoconduction material used for the PCSSs was a semi-insulating GaAs with thickness of 0.6mm. The resistivity in total darkness was $>5\times10^7\Omega\cdot$cm, the mobility was $>5500\mathrm{cm}^2/(\mathrm{V}\cdot\mathrm{s})$. The two electrodes were Au/Ge/Ni ohmic contacts and the distance of the two electrodes was 4mm. The transmission line is connected outside with two coaxial connectors as shown in Fig. 1. The Nd:YAG ns laser was used as triggers. The laser operated at a wavelength of 1064nm with a pulse width of 5ns, and the laser pulse energy ranged from μJ to mJ. 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.

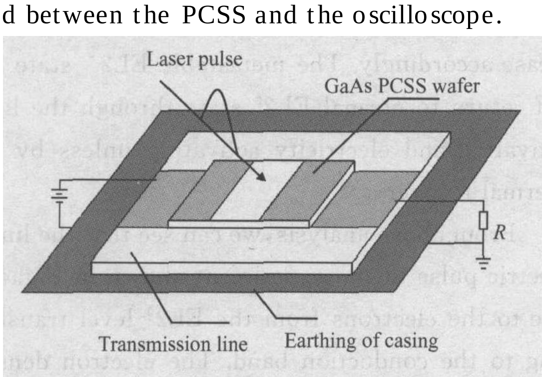

Fig. 1 Schematic of SI-GaAs photoconductive

When the PCSS was triggered by laser pulse energy of 0.8mJ, current waveforms shown in Figs. 2 and 3 are observed. These two figures correspond to two different biased electric fields of 2.0 and 6.0kV/cm, respectively. Whereas the PCSS was also triggered by laser pulse energy of 0.8mJ and the biased electric field is 9.5kV/cm, a clear corresponding peculiar electric pulse is captured, as shown in Fig. 4. It is quite interesting that the switch outputs a linear waveform firstly, and then after a delay-time of about 250ns, the PCSS gives a nonlinear waveform though the triggering laser pulse has gone out. It is indicated that the instance as shown in Fig. 4 is instability. In our test the SI-GaAs PCSS was series triggered 60 times with interval 5s, when the biased electric field was also fixed at 9.5kV/cm and triggering laser pulsed energy was in range from 0.5 to 1.0mJ, the superposed waveforms are captured as shown in Fig. 5. The delay-times between linear waveform and nonlinear waveform of about 20～250ns were observed.

Fig. 2 Waveform of linear mode X: 50ns/div, Y: 500mV/div

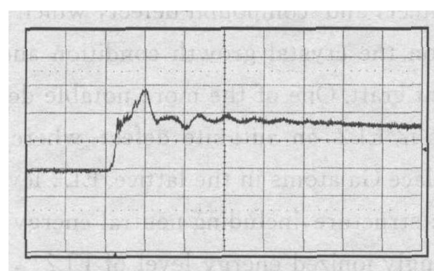

Fig. 3 Waveform of non-linear mode X: 50ns/div, Y: 500mV/div

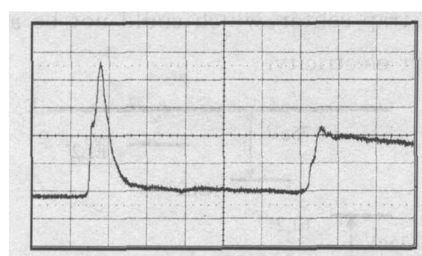

Fig. 4 Waveform of complex mode X: 50ns/div, Y: 500mV/div

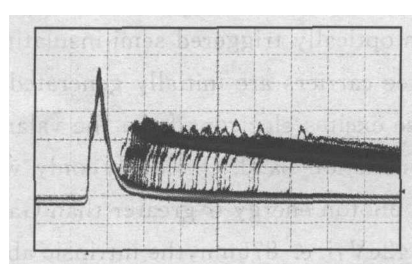

Fig. 5 Superposed waveforms of 60 times X: 50ns/div, Y: 500mV/div

3 Discussion

Base on our experiments, it is indicated that the delay time between linear waveform and nonlinear pattern is more longer than the width of triggering laser pulse. In other words, the second nonlinear waveform is generated while the trigger laser pulse has already gone out. Therefore, like the nonlinear pattern of the PCSSs (lock-on effect), this peculiar phenomenon is also related to the carrier avalanche mechanism.

For GaAs material the defects often play an important role in many physical process. The semi-insulating GaAs material also has many kinds of intrinsic-defects[9,10] such as anti-site defect, interspace-defect, and compound-defect, which closely depend on the crystal growth condition and after-treatment craft. One of the more notable defects of SI-GaAs is EL2, an anti-site defect, where As atoms replace Ga atoms in the lattice. EL2 level has a complex structure, including neutral energy level of $EL2^0$, singly ionized energy level of $EL2^+$, and the metastable state of $EL2^*$ as shown in Fig. 6. It is known that the metastable state of $EL2^*$ energy level is a trap center, which could not be activated by light or electricity.

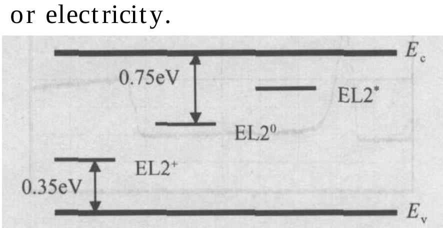

Fig. 6 Schematic of EL2 level structure

In an optically triggered semi-insulating GaAs switch, free carriers are initially generated when a light pulse excites electrons from the valance band to the conduction band. Obviously, only when the incidence photon energy is greater than GaAs band gap of 1.42eV, i.e. 876nm, the intrinsic absorption can take place. We define λ_0 (λ_0 = 876nm) is absorption limit of GaAs material. The laser wavelength in our experiments is 1064nm, which is out of the material absorbing range. For 1064nm laser there are at least two kinds of absorption mechanisms in SI-GaAs material. One of the mechanisms is the two-step-single-photon absorption[11,12], which is based on the EL2 energy level. Another is the double-photon absorption, which usually occurs at the condition of high power of triggering laser. In the process of two-step-single-photon abstraction, the neutral energy level of $EL2^0$ transforms into the metastable state of $EL2^*$ gradually. Photo-quenching experiments in SI-GaAs proved that the $EL2^0 \rightarrow EL2^*$ can availably take place at the irradiation photon energy range from 1.1 to 1.2eV. Because the photon energy of 1064nm laser is 1.167eV, the process of $EL2^0 \rightarrow EL2^*$ must occur in two-step-single-photon absorption. The $EL2^*$ is a trap center, which could not be activated by light or electricity, therefore the density of the $EL2^0$ will reduce continuously, and the $EL2^*$ density will increase accordingly. The metastable $EL2^*$ state can not return to normal $EL2^0$ state through the light activating and electricity activating unless by the thermal recovery.

From above analysis, we can see that the linear electric pulse in the experiment shown in Fig. 4 is due to the electrons from the $EL2^0$ level transferring to the conduction band. The electron density n_e in conduction band is approximate to the density of the EL2, and the density n_e can be expressed by[13]

$$n_e = \frac{E_{pulse}}{Adh\gamma\left(1 + \frac{\sigma_p^0}{\sigma_n^0} + \frac{\sigma_*^0}{\sigma_n^0}\right)} \quad (1)$$

where E_{pulse} = 0.8mJ is the energy of laser pulse, $h\gamma$ is the single photon energy, A = 0.5mm^2 is the GaAs sample area illuminated, d = 0.6mm is the GaAs thickness of sample material, $\sigma_n^0 = 1.5 \times 10^{-16}$ cm^{-2} is the optical capture cross section for electron transition from the EL2 level to the conduction band, $\sigma_p^0 = 1.39 \times 10^{-17}$ cm^{-2} and $\sigma_*^0 = 4.5 \times 10^{-17}$ cm^{-2} are the optical capture cross section for transitions between EL2 and the valence band and the metastable $EL2^*$ states. Hence, the conduction-band electron density of about $10^{16}cm^{-3}$ is calculated from above function. This theoretical value basically agrees with the EL2 defects density of $2\times10^{16}\sim4\times10^{16}cm^{-3}$.

After activated by the linear electric pulse shown in Fig. 4, almost all the EL2 defects will transfer to the metastable state of $EL2^*$. Only the thermal recovery can resume the $EL2^*$ to $EL2^0$. When $EL2^*$ changes into $EL2^0$ again, some of EL2 become electron traps ultimately and other EL2 become $EL2^+$ owing to the electricity compensate. In this process, the electrons are excited to the conduction band by the biased electric field, and these conduction-band electrons will form the Gunn domain owing to the negative differential mobility. In Gunn domain region the localized electric field will be enhanced and reachs the electric field threshold of avalanche impact ionization ultimately[12,14,15]. So, the charge avalanche multiplication process will take place and the SI-GaAs PCSS outputs a nonlinear waveform subsequently.

The delay time between the linear operation waveform and nonlinear operation waveform should be the recovery times for $EL2^*$ returning to the $EL2^0$, using

$$\tau_r = \frac{\exp\left(\frac{E_a}{kT}\right)}{c} \qquad (2)$$

the rough value of delay times can be estimated, where the $E_a = 0.34eV$ is the energy gap between $EL2^*$ and the $EL2^0$, k is the Boltzmann constant, c is the experience constant which is associated with temperature T, $c = 8.6\times10^{11}s^{-1}$ at the room temperature. Therefore, the recovery time of about 10^2 ns is calculated from Eq. (2), and this calculation result agrees with the experiment roughly.

Of course, for many applications this peculiar phenomenon may be baneful. To avoid this phenomenon, the GaAs photoconductive switch must be under thresholds of optical energy and biased electrical filed in linear model or above the thresholds in nonlinear model.

4 Conclusion

The semi-insulating GaAs PCSS triggered by 1064nm laser pulse could work at peculiar performed characteristics. At triggering conditions of 0.8mJ irradiated laser energy and 9.5kV/cm biased electric field, the switch gives a linear waveform firstly, and then after a delay-time of about 250ns, the GaAs PCSS outputs a nonlinear waveform again. The physical mechanism of this specific phenomenon is associated with the anti-site-defects of semi-insulating SI-GaAs and two-step-single-photon absorption. The delay time between linear waveform and nonlinear waveform is calculated, and the result matches the experiments.

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用 1064nm 激光脉冲触发半绝缘 GaAs 光电导开关的奇特光电导现象*

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摘要: 报道了用 1064nm 激光脉冲触发半绝缘 GaAs 光电导开关的一种奇特光电导现象. GaAs 光电导开关的电极间隙为 4mm,当偏置电场分别为 2.0 和 6.0kV/cm 时,用脉冲能量为 0.8mJ,宽度为 5ns 的激光触发开关,观察到开关输出的线性和非线性工作模式. 当偏置电场增至 9.5kV/cm,触发光脉冲能量在 0.5～1.0mJ 范围时,观察到奇特的光电导现象,开关先输出一个线性电脉冲,经过大约 20～250ns 时间延迟后,触发光脉冲消失,开关又输出一个非线性电脉冲. 这一奇特光电导现象的物理机制与半绝缘 GaAs 中的反位缺陷和吸收机制有关. 分析计算了线性与非线性电脉冲之间的延迟时间,结果与实验观察基本吻合.

关键词: 光电导开关; 半绝缘 GaAs; EL2 深能级

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