Transit Properties of High Power Ultra-Fast Photoconductive Semiconductor Switch

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Abstract: Experiments of a GaAs ultra-fast Photo-Conductive Semiconductor Switch (PCSS) are reported. Both the linear and nonlinear modes were observed when triggered by the μJ nano-second laser. The peak current could be as high as 560A. The rise time of the current pulse responses is less than 200ps when triggered with 76MHz femto-second laser.

Key words: ultra-short electromagnetic pulse source; photoconductive switch
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大功率超快半导体光电导开关的触发瞬态特性

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摘要: 报道了用 ns 和 fs 超快脉冲激光器触发 GaAs 光电导开关的实验结果. 用 μJ 量级的 ns 光脉冲触发 3mm 间隙的 GaAs 光电导开关, 观察到线性和非线性工作模式, 峰值电流达 560A. 当用重复率为 76MHz 的 fs 激光脉冲串触发同一器件时, 电流脉冲上升时间小于 200ps.

关键词: 超快电磁脉冲源; 光电导开关
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1 Introduction

Photo-Conductive Semiconductor Switches (PCSS's) are a kind of hybrid devices which comprise photoconductive semiconductors (such as GaAs) and ultrafast lasers. Such switches offer unique properties as ultrafast response (picosecond rise/fall), GHz repetition rate, gitter free, small parasitic inductance and capacitance, insulated triggering, wide dynamic range being suitable for various transmission lines etc. Besides, PCSS can operate at high voltage, high current, which is the most promising next generation devices in the high power electrical pulse generation and reshaping substituting traditional gap discharging, thyristors and junction devices. It has wide applications in ultra-wide-band microwave generators and electromagnetic weapons.

Researches on PCSS's acting as an electromagnetic missile can be seperated into several stages; from 1972 to the beginning of 1980's, the recovery and research of the ultra-fast response of PCSS's[1]; from the mid 1980's, PCSS's were found their application in low power ultra-fast electronics, there were also some practical results of applying PCSS's in the area of high power electromagnetic missile generator, ultra-wide-band microwave and millimeter-wave. During these periods, the high gain mode of PCSS (lock-on effect or nonlinear mode) was found under a high electric field[2,3].

After the 1990's, researches on PCSS's are concentrated on the following three aspects: (1) Researches on the mechanisms and application of the lock-on effect: Experiments on PCSS's showed that under the high electrical field, the avalanche process was involved which caused the high current rise within nano-second time and low trigger light intensity (10^{-4} of that in the linear mode); High conductivity state would be sustained after the light trigger until the outside circuitry could not provide the above threshold electrical field[4]; Fast recovery could be realized by shortening the carrier life time. (2) Device technology of PCSS: two electrodes configurations were developed with one of double- side mesh electrode (or transparent electrode) for vertical PCSS and all the other single-side electrode for surface PCSS. Particularly, triggering light energy was further lowered with line triggering or dot triggering for surface PCSS. (3) Application of PCSS's: the properties of the combining PCSS's with various kinds of transmission line. Ultra-wide-band microwave generator has been realized, and the application of PCSS's keeps on enlarging[5].

2 Experimental

The material used for the PCSS was a semi-insulating GaAs with thickness of 0.6mm. The resistivity in the darkness was higher than $5\times10^{7}\ \Omega\cdot cm$, and the mobility was more than $5500cm^{2}/(V\cdot s)$. The sample was size 9.0×6.0mm, and the electrode dimension 6.0×3.0mm. The distance between two electrodes was 3mm. The GaAs was placed on the substrate of a copper board with transmission line. The transmission line was connected with outside by two coaxial connectors. Multiple transparent layers were used as the top insulating layer. Both Ti∶sapphire fs laser and Nd∶YAG frequency-doubled ns laser were used as triggers. The Ti∶sapphire laser operated at a wavelength of 780nm, a pulse width of 120fs, a repetition rate of 76MHz and a pulse energy of 7.6nJ. While the Nd∶YAG frequency-doubled laser at a wavelength of 532nm, a pulse width of 8ns, and variable pulse energies in the range of μJ to mJ.

The storage oscilloscope used was HP54720D. A 60dB coaxial attenuator with a bandwidth of 0—18GHz was used between the PCSS and the oscilloscope. A good temperal characteristic was observed when the switch was under the field of 12kV/cm and triggered with the fs laser pulse strings. A clear corresponding current pulse string was captured, as shown in Figure 1(a). The rise time of the pulse was less than 200ps as shown in Figure 1(b), this rise-time was limited to the bandwidth of the coaxial cable used in this experiment. The same switch was triggered by 532nm frequency-doubled Nd∶YAG laser. Current waveforms were shown in Figure 2(a) and 2(b). Figure 2(a) shows the linear mode of the PCSS while Figure 2(b) the nonlinear mode (lock-on mode).

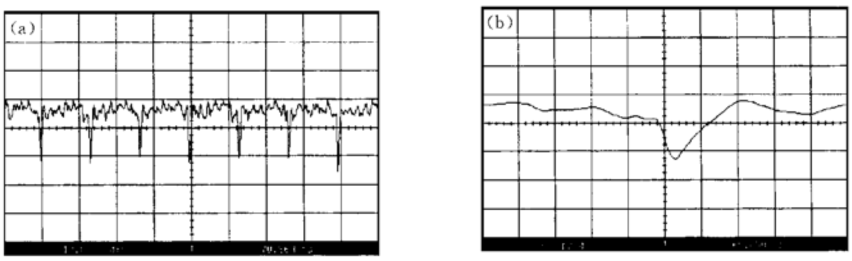

FIG.1 (a) Current Pulse String Triggered by Femto-Second Laser Pulse (Y/div 18mV, X/div 10ns); (b) Rise Time of the Pulse was Less than 200ps (Y/div 18mV, X/div 500ps).

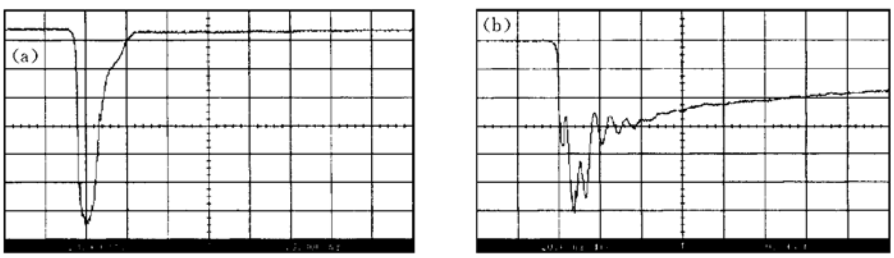

FIG.2 (a) Linear Mode Current Waveform (Y/div 4V, X/div 20ns); (b) Lock-on Mode Current Waveform (Y/div 4V, X/div 20ns).

Our experiments proved that when the PCSS was triggered by the frequency-doubling Nd∶YAG laser, if the applied electrical field was below 4.3kV/cm, only the linear mode could be obtained no matter how high the laser energy was. The current pulse has the same rise time and pulse width as the trigger laser pulse. The PCSS recovered its high resistivity state after the light trigger. When the electric field was larger than 4.3kV/cm and the trigger laser energy bigger than 1.2mJ, the PCSS would turn into the lock-on mode. From Figure 2(a), the current was seen about 560A.

3 Results and Discussion

Although the intrinsic GaAs has a breakdown strength of 250kV/cm, there are a lot of factors that may cause the device to breakdown below it. For example, surface lightening and thermal breakdown may be the causes of sub-threshold breakdown. The sustain voltage under the darkness state is not determined by the electrodes gap only. Without insulation protection, the breakdown strength would be less than 10kV/cm due to the surface lightening. The maximum voltage that can be applied to PCSS is generally determined by the factors, such as semiconducting material, geometric shape of the material, structure and shape of the electrodes, and the protection methods etc. Using silicon nitride and organic silicon gel double structures, as what we used in this experiment, the PCSS shows not only a good optical property (transparent), but also good thermal expansion resistant property and good insulating property. The darkness breakdown strength is increased to 35kV/cm.

Under the low electrical field, the PCSS works in a linear mode. One photon generates one electron-hole pair (EHP). The resulting current pulse has the same shape as the trigger light one. The EHP recombination experiences an exponential decay with the time. After the light triggering, the PCSS will recover its high resistive state. The linear mode PCSS is greatly limited by its requirement of high-energy light pulse triggering.

Under the high electrical field, the PCSS operates in the high gain mode or lock-on effect. The lock- on effect can be separated into three stages, ie. triggering, sustaining and recover. When the PCSS is under an electric field higher than the threshold field (5—100kV/cm) and triggered by the short light pulse with energy greater than the light threshold (μJ), it will enter the triggering state. The thresholds of the electrical field and light energy are determined by the property of semiconductor materials. The electric field threshold was inversely proportional to the light energy threshold. For the 1.5cm long Cr∶GaAs PCSS triggered by 532nm wavelength laser with 5ns in width, the electric field threshold was in the range of 5—65kV/cm, while the corresponding light energy threshold was in the range of 600—20μJ. When there is no light triggering, the high resistive state will remain until 143kV/cm of the electric field. Under the high electric field, the triggering light energy is just 1/500—1/1000 of that for under the low electric field. Low light triggering means high gain of carrier generation. One photon may generate as many as 10^3—10^5 EHPs. Low light triggering makes it practical to replace the bulky YAG laser with the LDA, and to trigger the PCSS by fiber pigtails with single-spot or multiple-spots method. The multiple-spots triggering method can be used to control the number of channels and the current density of each individual channel. For the lock-on effect under the low light triggering, the current rise is strongly dependent on the triggering electric field. Under the extremely high electric field (4—5 times of that for the starting of lock-on effect), the current rise can be much shorter than the triggering light pulse. When PCSS was triggered into its lock- on mode, the voltage across the PCSS was dropped to a non-zero value within several nano-seconds. After the light pulse, the switch will remain its low resistance state, and the current will be kept until the external circuitry could not provide a certain electric field which is called lock-on electric field. Similar to the threshold field, lock-on field is also determined by the materials. For GaAs PCSS, the lock-on field is ranging between 3.5—8.5kV/cm. During the sustaining period, the resistance of the PCSS equals to the lock-on voltage divided by the current. Using the operation, the switch is always the same voltage, like the Zener diode. After the light pulse, there is a continuing current flow inside the PCSS, this means there exists a carrier multiplication mechanism which is totally different with the linear mode of PCSS. Meanwhile, one or more fiber currents could be observed during the sustaining period. Lock-on effect is not destructive. Whenever the field is less than the lock-on field, the switch will recover. For a 1.5cm long Cr∶GaAs PCSS, the recovering time is around some dozens of nano-seconds.

4 Conclusion

Experiments on a 3mm gap GaAs PCSS triggered by ns and fs lasers were performed. The GaAs PCSS shows a good and stable operation. It is an all-solid state device with an all-solid-state insulation structure, which can effectively avoid the breakdown caused by the surface lightening and provide the adaptability to the thermal expansion under the high current pulse. Under 13.6kV/cm field and triggered by 900μJ ns laser, the 3mm gap GaAs can achieve a current as high as 560A in the linear mode. Both linear and nonlinear modes were demonstrated. When triggered by 7nJ fs laser at 76MHz repetition rate, the switch showed a good temperal response. The current rise time is less than 200ps.

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