The Effect of Photoconductive Semiconductor Materials in Improving the Resolution of Femtosecond Streak Camera

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Abstract. In this study, through the research on the effect of photoconductive semiconductor materials in improving the resolution of femtosecond streak camera, the effective value of applying photoconductive semiconductor materials to femtosecond streak camera is discussed and analyzed, and the effectiveness of photoconductive semiconductor materials in improving the resolution of femtosecond streak camera is verified. Method: In this study, first of all, the generation and recombination of carriers in semiconductors are studied. Solving the continuity equation is applied to further explore the law of the motion of carriers. Later, photoconductive semiconductor materials are used in the preparation of switching devices and scanning circuits. After that, the prepared circuit module is tested by dark current. The main purpose is to realize the resistance of the circuit switch in the intrinsic state and the dark state withstand voltage ability of the circuit switch. Results: It is found that the dark state withstand voltage of each switch can exceed 6000V. In addition, it is found that the current value of the switch under different light is different. When in the natural light, the current value is large. When it is in the state of shading, its current value is relatively small. The efficiency of all three switches is over 50%. The efficiency of nonlinear model is obviously higher than that of linear model, which can be more than 90%. By applying the semiconductor material to the femtosecond streak camera, the scanning circuit can be optimized effectively to meet the high standard requirements of the femtosecond streak camera for the scanning circuit, which has certain advantages, and has certain value and significance for improving the resolution of the second streak camera.

1. Introduction
Ultrafast diagnosis technology is a fruitful and enduring research topic. In the research process of more than 100 years, there are many kinds of ultrafast diagnostic equipment developed by people, and the scope of diagnosis ranges from the microsecond level to the femtosecond level [1-3]. According to the working mechanism, three kinds of ultrafast diagnostic equipment have been developed. The first one is the optical mechanical high-speed camera, through the high-speed movement of the mechanical components in the camera to achieve the instantaneous capture and imaging of the super fast target. The second is electro-optical or magneto-optical shutter high-speed camera, which is based on the electro-optical or magneto-optical modulation effect of materials, a shutter type high-speed camera, such as a Kerr box camera, is made. The third is a high-speed camera with image converter. A high-speed camera
based on the vacuum image converter technology senses the ultrafast light signal through the photocathode and converts it into an electrical signal, which is either deflected by scanning or directly imaged on the fluorescent screen through pulse gating [4-6]. Among the three types of high-speed camera, the high-speed camera with image converter has the widest diagnosis range, the best performance and the widest application, which is the research hotspot of the ultra fast diagnosis technology [7].

As the best indicator to measure the technical level of streak camera, time resolution has always been a hot competition in the field of ultrafast diagnosis in various countries [8]. As early as the 1980s, the temporal resolution of the streak image tube has entered the femtosecond level. However, there are not many countries that can develop the femtosecond streak camera according to the design results. The Institute of general physics of Russian Academy of Sciences has been in the leading position in the development of streak camera. In terms of the development of the femtosecond time-resolved streak camera, the institute has been successful since the 1990s (the former Soviet Union), with a time resolution of 200fs [9] for the FV-FS-M type streak tube. Hamamatsu company of Japan is the research institute with the highest level of standardization and commercialization of streak camera. Similarly, in the 1990s, Hamamatsu company has reported a streak image converter with a time resolution of 180fs. In recent years, the company has launched a commercial femtosecond streak camera with a time resolution of 200fs [10]. In China, the professional development units of streak camera include Xi'an Institute of Optics and mechanics of Chinese Academy of Sciences and Shenzhen University. Among them, the research and development of the streak camera of Xi'an Institute of Optics and mechanics began in 1963. In the past 50 years, Xi'an Institute of Optics and mechanics has developed many kinds of streak cameras, whose diagnosis range is from nanosecond to picosecond.

In this study, photoconductive semiconductor materials are used in the preparation of scanning circuit because of the high requirement of scanning circuit for femtosecond streak camera. First of all, the principles and approaches of the generation and recombination of carriers in semiconductors are further analyzed. After that, the numerical simulation and simplification of linear model are carried out. Then, on this basis, circuit modules and devices are prepared. Finally, the dark current test method is applied to verify the effectiveness of photoconductive semiconductor materials. It is found that the application of photoconductive semiconductor materials can meet the high requirements of scanning circuit to some extent, and can improve the performance of optimized scanning circuit. Whether it is in the nonlinear mode or in the linear mode, the efficiency of voltage conversion and the efficiency of circuit switch have been improved. It is proved that the photoconductive semiconductor material can meet the requirements of femtosecond streak camera.

2. Method

2.1. Generation and recombination of carriers in semiconductors

The core of semiconductor devices is the generation and recombination of carriers. The most important basis of its operation is the energy band theory of solid, which includes two kinds. The first is the guide band and the second is the price band. Only electrons in the conduction band and holes in the valence band can promote the generation of carriers. When it is at absolute zero, the valence band of semiconductor will become full band. On the contrary, the conduction band will become empty. However, there is a disadvantage that the electrons in the full band do not have conductivity and no carrier. As shown in figure 1, the states of semiconductors are respectively at room temperature of absolute zero, in the intrinsic state and in the excited state. When it is at absolute zero, the semiconductor can be in the intrinsic state without any doping, and some electrons will migrate to the conduction band and leave holes. When it is in this state, the carrier concentration of the conductor will decrease, but the resistivity will not change, and it is still in a very high state. When excited, the electrons move all the way to the conduction band, leaving a large number of holes behind, and the concentration will rise quickly, and finally change to the state of conductor.
There are two ways semiconductor can generate carriers. The first is electrical injection. The second is light injection. The main way of application in this study is light injection. Its principle is to modulate the conductivity of semiconductor by using light.

There are four mechanisms of carrier recombination: direct recombination, indirect recombination, surface recombination and Auger recombination. Among them, direct recombination means that the electrons in the conduction band will fall directly into the valence band and can be combined with holes, so the direct coincidence rate of carriers can be calculated. The equation is as follows:

\[
U_d = k_d (pn - n_i^2)
\]

Among them, \( k_d \) represents the direct compound probability of electron and hole, the concentration of hole is represented by \( p \), and the concentration of electron is represented by \( n \).

Indirect recombination means that the electrons in the conduction band and the holes in the valence band can be compounded by other auxiliary means. In this process, the most important auxiliary body is the third level in the band gap. Therefore, the equation for calculating the indirect recombination rate is as follows:

\[
U_i = \frac{(pn - n_i^2)}{\tau_n (p + n_i) + \tau_p (n + n_i)}
\]

In the equation, \( \tau_n \) represents the lifetime of electron, \( \tau_p \) represents the lifetime of hole, the concentration of hole is represented by \( p \), and the concentration of electron is represented by \( n \).

Auger recombination is the recombination of carriers in the process of transfer from high energy level to low energy level. At this time, the remaining energy will be transferred to other carriers. Carriers move to higher energy levels. When transferred to the lower energy level, it will release energy again. The calculation equation of the composite rate is as follows:

\[
U_E = (\gamma_e n + \gamma_p p)(pn - n_i^2)
\]

The consciousness of surface recombination is that the recombination central energy level of forbidden band will be produced in the process of recombination. In general, the speed of composite velocity is expressed by surface composite velocity. The equation is as follows:

\[
S_p = \sigma + \nu_f N_{st}
\]

In the equation, the total number of composite centers is represented by \( N_{st} \).

2.2. Preparation of photoconductive switching devices

For the photoconductive switch device, its main structural parameters are electrode gap \( G \), electrode length \( L \), switch width and switch thickness, electrode fillet radius, etc. Among these parameters, the withstand voltage of the switch is determined by the electrode gap, but it should also meet the requirements of the circuit. In addition, the electrode gap should be combined with the spot size of the
trigger pulse. In this experiment, in order to prevent the local breakdown of the switch surface, it is necessary to convert the chamfering of the electrode at right angles, and the radius of the chamfering is usually less than 0.5mm. For the switch body material, it is necessary to strictly require its thickness, which must be greater than the depth of light absorption. Not only the structural parameters are determined, but also the materials used in the switch are strictly selected.

2.3. Preparation of scanning circuit module
As a transmission system, scanning circuit is mainly formed by high frequency electromagnetic pulse. It is very fast for the scanning circuit, and the signal spectrum is relatively wide. Therefore, two principles should be followed in the preparation of circuit modules. The first principle is to spread all the high frequency signals in the microstrip line or coaxial line. PCB should be made into double-layer board. One side is in contact with the ground. The characteristic impedance of the microstrip line is designed to be 50 ohms. The second principle is to select the components with relatively small parasitic parameters. In this way, the bandwidth of the circuit can be improved. Moreover, the voltage withstand value should be high enough to meet the conditions. The voltage withstand value of the chip element used in this experiment is 3000V. During circuit scanning, two synchronous pulses are connected to the 50 ohm coaxial line through the SMA interface. GaAs has a certain sensitivity to light, so it is necessary to pay attention to protect it from light when preparing it. In addition, 705 transparent insulating adhesive can be coated on the surface in order to prevent the same surface photoconductive switch from discharging along the surface.

2.4. Definition and simplification of continuity equation
There are two ways to study the motion of carriers. The first is to solve the continuity equation, and the second is Monte Carlo simulation. The semi quantitative research object of this study is mainly the generation, diffusion and compound law of downcomer in linear mode of photoconductive switch, the method of solving continuity equation is chosen.

In order to analyze the internal photoelectric effect of semiconductor, the continuity equation is simplified. Before that, it is necessary to simplify the physical model in four cases. The first case is that the external light can irradiate the surface of the semiconductor uniformly, and the carriers will only diffuse in the same direction. The second case is that this experiment only studies the generation, recombination and diffusion of carriers. In the third case, other possible ways of carrier generation are not considered, only focus on the carrier generated by the cause. The fourth situation is that this experiment will take into account the four composite approaches. If the light beam is injected along the z-axis, the carrier generation rate is expressed in g(z, t). The simplified continuity equation is as follows:

\[
\frac{\partial p(z, t)}{\partial t} = D_p \frac{\partial^2 p}{\partial z^2} - k_g (pn - n_i^2) - \frac{(pn - n_i^2)}{\tau_p (p + n_i) + \tau_p (n + n_i)} + g(z, t) \tag{5}
\]

\[
\frac{\partial n(z, t)}{\partial t} = D_n \frac{\partial^2 p}{\partial z^2} - k_g (pn - n_i^2) - \frac{(pn - n_i^2)}{\tau_n (p + n_i) + \tau_n (n + n_i)} + g(z, t) \tag{6}
\]

In the equation, p and n represent the concentration of electrons and holes. Dp and Dn represent the diffusion coefficients of holes and electrons. The equations of the boundary conditions are as follows;

\[
P(0, t) - n_i = \frac{D_p}{s_p} \frac{\partial p}{\partial z} \bigg|_{z=0}, p(\infty, t) = n_i \tag{7}
\]

\[
n(0, t) - n_i = \frac{D_p}{s_n} \frac{\partial n}{\partial z} \bigg|_{z=0}, p(\infty, t) = n_i \tag{8}
\]
3. Results and discussion

In this study, the prepared circuit modules are tested for dark current. Using this method, not only the resistance of the circuit switch when it is in the eigenstate can be known, but also the dark state withstand voltage ability of the circuit switch can be clearly realized. The schematic diagram of dark current test is shown in figure 3. The main test object is the dark current of several switches. During the test, the + HV and - HV are adjusted synchronously. Among them, the main function of R1 and R2 is to limit current, and its resistance value is 470K Ω. When the switch is in the intrinsic state, its resistance value will far exceed R1 and R2, so the voltage drop on R1 and R2 will not be included in the test. The voltage difference between + HV and - HV is taken as the voltage at both ends of the switch, and then the acute current of microammeter is recorded. After testing, it can be concluded that the dark state withstand voltage of each switch can exceed 6000V. In addition, it is found that the current value of the switch under different light is different. When in the natural light, the current value is large. When it is in the state of shading, its current value is relatively small. The final test results are shown in figure 4 and figure 5. It can be seen from the figure that the current degrees of the three switches are very small when they are in the blackout state, especially No. 1 and No. 3. The current of switch 3 is kept at about 1 μ A. For switch 2, its dark state resistance is very large, indicating that the current is also very small. When the switch is in the non shading state, it can be seen that the current of the three switches will increase. Among them, the current of switch 3 is the largest. In addition, when the bias voltage exceeds 6000V, the other two switches will discharge along the surface.
With the development of science and technology, the appearance of femtosecond streak camera has brought a lot of benefits to people. As the fastest time resolution diagnostic equipment, its resolution can even reach femtosecond level. Among them, the femtosecond streak tube has a decisive influence on the time resolution of the femtosecond streak camera, but the femtosecond streak tube has a high demand and standard for the slope of the scanning voltage and the triggering shake. Conventional scanning circuit has many disadvantages. In recent years, many experts and scholars have carried out in-depth research based on this, but there is still no significant breakthrough. Therefore, it is very important and necessary to study the scanning voltage in femtosecond streak tube.

In this study, photoconductive semiconductor materials are used in the preparation of scanning circuit to optimize the scanning voltage. First of all, the principles and approaches of the generation and recombination of carriers in semiconductors are analyzed. After that, the circuit is optimized by applying the numerical simulation and simplification of linear mode. Finally, the effectiveness of photoconductive semiconductor materials is verified by dark current test. After testing, it is found that

**Figure 4.** Dark current test results of photoconductive switch in non shading state

**Figure 5.** Dark current test results of photoconductive switch under shading state
the dark state withstand voltage of each switch can exceed 6000V. The current value of the switch under different light is different. When the current value is larger in the natural light than in the dark state, the current value is smaller, and the efficiency of the three switches is more than 50%. The efficiency of nonlinear model is obviously higher than that of linear model, which can be more than 90%. It can be seen that the application of photoconductive semiconductor materials can further optimize the performance of scanning circuit. No matter in any mode, the efficiency of voltage conversion and the efficiency of circuit switch have been improved. It is proved that photoconductive semiconductor material is of great value to optimize the resolution of full femtosecond streak camera.

4. Conclusion
In this experiment, through the use of photoconductive semiconductor materials for the preparation of scanning circuit, it is found that photoconductive semiconductor materials can avoid the shortcomings of traditional scanning circuit, optimize and improve its performance. This is mainly reflected in the application of photoconductive semiconductor materials. The voltage of the scanning circuit and the efficiency of the switch have been effectively improved, which can further improve the time resolution of the femtosecond streak camera by optimizing the femtosecond streak tube. However, all the tests in this study belong to single trigger mode, but femtosecond streak camera requires the repetition frequency of scanning circuit to be 1kHz ~ 5KHz. Therefore, in the future research, it is necessary to pay attention to this point. This study is still in the experimental exploration stage, without engineering design, which will also be the work to be carried out in the follow-up study.

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