V-T/I-T characterization of photoconductive semiconductor switch

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Abstract

Several ten nanometers width TiOx wires was fabricated on the surface of 3~5nm thick Ti film. It was used as insulator/energy barrier between the electrodes to substitute the air gap of traditional type photoconductive semiconductive switches (PCSS). The electrodes and substrate’s materials are Ti-Au and LT-GaAs respectively. The simulation result indicated that the LT-GaAs PCSS doesn’t work in the linear mode absolutely when it is triggered by Femtosecond Laser with about 10 voltages electric field bias. In the tail of the voltage or current output characteristic of the PCSS, another little positive peak appeared with a short time delay after the main linear pulse. This phenomenon is different from the traditional switch. In this paper, this phenomenon is analyzed and the method to avoid such kind of non-linearity output is discussed.

Keywords: Measurement and machining, photoconductive semiconductor switch (PCSS), electro-optic sampling (EOS) measurement, AFM tip-induced anodic oxidation, characterizing

1. Introduction

How to improve the speed of the ultra fast photoconductive semiconductor switches (PCSS) is the key question because the PCSS plays an important role in the high speed electro-optic sampling measurement method and in the Terahertz researches [1-5]. Decreasing the moving distance of the carriers is a considerable method besides substrate material selection and increasing bias voltage between the PCSS’s electrodes. Most kinds of the PCSS are based on the circuit structure of the micro belt photoconductive switches reported in 1975 [6]. This kind of PCSS has relative lower voltage conversion efficiency. The materials of such PCSS’s substrate are nearly all the silicon-on-sapphire (SOS) which has radiation damage [7]. It is indicated out that GaAs has advantage over the traditional silicon based on material analysis [8,9]. Its electronic mobility is 5-7 times higher than the silicon (in practice, it is the main transference mode of the carriers). GaAs has the advantages such as wider forbidden band, direct belt crack, and lower power consumption [10,11]. Therefore, in this paper, GaAs is used as the substrate material of PCSS.

Traditional PCSS employs narrow air gap as the insulator between the electrodes, shown in Figure 1(a). The gap is about several to several tens microns normally because of the lithography etching method. But it could not be made narrower because of the edge effect and aerial discharge. Therefore, traditional type PCSS should keep relative wider air insulator and higher bias voltage. Such gap enlarged the carrier’s moving distance and limited the PCSS’s speed within several tens ~ several picoseconds scale. The micro PCSS under studied is based on metal-insulator-metal conjunction. It is designed and trial fabricated via lithography and atomic force microscopy (AFM) tip-induced anodic oxidation techniques [12,13]. Titanium (Ti) belts formed on the surface of the LT-GaAs substrate and fabricated by lithography are used as the signal transmission lines and electrodes. The Ti oxide wire fabricated by AFM on the Ti belt is used as insulator between the electrodes. TiOx wire can substitute the air gap of the traditional PCSS. The width of the oxide is smaller than 100nm and can be narrowed to several tens nanometers. The improved PCSS is shown in Figure 1(b) and the output characteristics of it were simulated and discussed in the paper.
2. Simulation of the output characteristic of the MIM type PCSS

Figure 2 shows the circuit model and the equivalent electrical circuit which can visually explain the output electric pulse transient behavior in detail. The gap capacitance is $C(t)$, the gap resistance of photoconductive switch is $R_s(t)$ and the characteristic conductance of the transmission line is $Z_0$. If the electrodes contact the substrate purely resistively, the output voltage and resistance are then given [14] by

$$V_{out} = V_{in} \frac{Z_0}{2Z_0 + R_s(t)}$$

and

$$R_s(t) = \frac{L^2}{q[N(t)\mu_n + P(t)\mu_p]} + R_0$$

Where, $L$ is the length of the gap, $N(t)$ is the number of the photo-induced electrons, $P(t)$ is the number of the photo-induced holes, $\mu_n$ is the mobility of the electrons, $\mu_p$ is the mobility of the holes, $q$ is the electron or hole charge. According to the theory of semi-conductive photoelectrons, the changes of electron and hole should meet the continuity equation [15] in general cases.

$$\frac{\partial n}{\partial t} = \mu_n n \frac{\partial E}{\partial x} + \mu_n E \frac{\partial n}{\partial x} + D_n \frac{\partial^2 n}{\partial x^2} - \frac{\Delta n}{\tau_n} + f_n$$

$$\frac{\partial p}{\partial t} = -\mu_p p \frac{\partial E}{\partial x} - \mu_p E \frac{\partial p}{\partial x} + D_p \frac{\partial^2 p}{\partial x^2} - \frac{\Delta p}{\tau_p} + f_p$$

Where $\tau_n$ and $\tau_p$ represent the compound life of electron and hole respectively as both of them are non-balance current carriers; $f_n$ and $f_p$ represent their excitation rate, $D_n$ and $D_p$ respectively represents their diffusion coefficient. $n_0$, $p_0$, $\Delta n$, and $\Delta p$ represent the equilibrium concentration of electron and hole and their increased concentration respectively. In principle, the change of current carriers’ density under the dissimilar condition along the time can be calculated from Equation (3),
and then the ultra short output electric pulse transient behaviour can be explained. As it is very difficult to solve Equation (3) strictly, it must be simplified under the essential characteristic.

According to the working characteristic of photoconductive switch, the following suppositions to the continuity equation are proposed: 1) the electric field of PCSS’s gap is symmetrical and is mainly along X direction, \( E = \frac{V_{in}}{L} \), \( V_{in} \) and \( L \) are the bias and diffusion length of the carriers; 2) the material of the substrate is symmetrical, thus equation concentration has no relation with \( x \), and the carriers concentration of \( n \) and \( p \) in Eq. (3) can be replaced by \( \Delta n \) and \( \Delta p \); 3) according to Eq. (3), the continuity equation has both diffusion and excursion, and their ratio \( m \) is \( \frac{\mu_n}{\mu_p} \); 4) the contact between the electrodes and the semiconductor is purely resistive; 5) the ultra short pulse laser excite the PCSS’s semiconductor substrate. Its temporal and spatial distributions are the Gaussian distribution. Based on the hypotheses, Eq. (3) can be simplified to

\[
\frac{\partial \Delta n}{\partial t} = \frac{V_{in}}{L} \frac{\partial \Delta n}{\partial x} - \frac{\Delta n}{\tau} + f
\]

\[
\frac{\partial \Delta p}{\partial t} = -\frac{\mu_p}{L} \frac{\partial \Delta p}{\partial x} - \frac{\Delta p}{\tau} + f
\]

Where, \( f = \frac{\alpha p(\gamma)}{h v} = \frac{\alpha p_0(x, t)(1-R) \exp(-\alpha v)}{h v} \), and \( p_0(x, t) \) is the light pulse strength, \( R \) is the optical reflectance of the PCSS material, \( \alpha \) is the absorption coefficient, and \( v \) is the light frequency. Using the boundary condition \( \frac{\partial \Delta n}{\partial x}|_{x=\pm \infty} = 0 \), the initial condition \( \Delta n(x,0) = 0 \), and relation between \( R \) and \( \alpha \), Equation (4) can be resolved and then the relation between different parameters and pulse characteristic can be obtained.

The substrate material is low-temperature (LT) grown GaAs whose carries’ life is 0.4ps. When the femto-second Laser is used to excite carriers, the parameters [14] are: \( \mu_n = 0.88 \text{ m}^2/\text{V·s} \), \( \mu_p = 0.035 \text{ m}^2/\text{V·s} \), \( \tau = 0.4 \text{ ps} = 4 \times 10^{-13} \text{ s} \), \( \lambda = 800 \text{ nm} \), \( h v = 2.49 \times 10^{-19} \text{ J} \), \( T = 50 \text{ fs} = 5 \times 10^{-14} \text{ s} \), \( \alpha = 10^6 \text{ m}^{-1} \), \( R = 0.28 \), \( V_{in} = 10 \text{ V} \), \( L = 100 \text{ nm} = 1 \times 10^{-7} \text{ m} \), and the energy of the laser pulses \( I_0 \) is 1mJ.

Based on the parameters mentioned above, by resolve Eq. (4), the concentration expressions \( N(t) \) and \( P(t) \) of electron and hole carriers can be obtained.

\[
N(t) = 3.26 \times 10^{23} \left\{ (1.25 \times 10^{-9} e^{-4x \times 10^8 t^2} - 3.91 \times 10^{-24} e^{-4x \times 10^8 t^2})
+ e^{-2.5 \times 10^7 t} \right\}
+ (6.92 \times 10^{-9} - 2.77 \times 10^{-21}) e^{-2x \times 10^7 (8.8 \times 10^{-7} + 5 \times 10^{-9} t)^2}
+ (2.77 \times 10^{-21} - 6.92 \times 10^{-9}) e^{-15.488 \times 10^7 t^2}
\}
\]

\[
P(t) = 3.26 \times 10^{23} \left\{ (4.69 \times 10^{-8} e^{-4x \times 10^8 t^2} - 1.46 \times 10^{-22} e^{-4x \times 10^8 t^2})
+ e^{-2.5 \times 10^7 t} \right\}
+ (-1.03 \times 10^{-8} t - 4.12 \times 10^{-21}) e^{-2x \times 10^7 (-3.5 \times 10^{-8} + 5 \times 10^{-9} t)^2}
+ (1.03 \times 10^{-8} t - 4.12 \times 10^{-21}) e^{-2.45 \times 10^7 t^2}
\}
\]

Because the contact between the electrodes and the semiconductor is purely resistive, so \( R_s \neq 0 \), then \( R_s \) can be rewrited as \( R_s(t) \approx \frac{L^2}{q[N(t)\mu_n + P(t)\mu_p]} \), and the output of voltage and current are

\[
V_{out} = V_{in} \frac{Z_0}{2Z_0 + \frac{L^2}{q[N(t)\mu_n + P(t)\mu_p]}}
\]
In this paper, the resistance of the transmission line is \( Z_0 = 50 \Omega \), \( V_{in} = 10V \). According to the upper parameters, and Eq. (7)~ Eq. (8), the V-T and I-T characteristics are obtained via Matlab simulation, as shown in Figure 3 (a), (b) and (c).

![Figure 3 (a) V-T characteristic, (b) I-T characteristic, (c) V-T characteristic with different width of Oxide.](image)

3. Discussion

From Figure 3 (a) to (c), it can be seen that the output characteristic of the GaAs PCSS is not the complete linear output. After a linear peak output, a non-linear peak appears and the former is much higher than the latter. This indicates that the latter is not the characteristic output surely. The nonlinearity becomes more distinct along with the insulator’s width increasing. The possible reasons of the non-linear output are as follows:

1. Double photon absorption: During the interaction of the PCSS material and the laser, as one kind of non-linear effect, both of the two photons whose phases are correlative can stimulate an electron from the valence band to the conduction band. This nonlinear interact has an effect on the coherent radiation whose energy \( h\nu \) is less than \( E_K \) is absorbed.

2. Thermal absorption: In the material, the carriers which absorb the energy of light hit the phonons to produce heat because the semiconductor is a sort of thermo-sensitive material. Namely, the carriers get energy from thermal vibration of crystal lattices and then transite to the conduction band. Electron and hole must release certain energy from their compound process. In this process, the energy is transmitted to the third party by the interactivity.

Moreover, during the illumination period of the Laser, the electric conductance of sample increases unceasingly along with the exposure time. This is because the laser illumination induces the thermal reaction. When the laser power density is bigger than 64 w/cm\(^2\), the laser stops exposure. The material resistance can not recover immediately to the original value, but get back slowly, because the thermal accumulation needs certain time to release. From the above analysis, the thermal absorption can be considered as the main reason of the PCSS. Therefore, to establish the good radiation

4. Conclusion

In this paper, theoretical output characteristics of PCSS on GaAs substrate are simulated and analyzed. Through the analysis, there is a peculiar non-linear phenomenon. The reasons for this phenomenon are explained. The main reason is the thermal absorption. At last, the solution is
efficiency. The narrower the width of TiOx wire is, the half width of the main output curve becomes

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