Studying of the Dipole Characteristic of THz from Photoconductors

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Abstract — Under the different experimental conditions, THz waveform which was generated by the different GaAs photoconductive switch provided with diverse carrier lifetimes triggered by femo-second laser pulse are calculated. The results indicate the main course of the dipole characteristic of THz waveforms emitting from low-temperature grown GaAs is the lifetime of optical-generated carriers less than the generation time; To SI-GaAs photoconductive semiconductor switches with the lifetime of optical-generated carriers more than 100 ps, the dipole characteristic of THz waveforms is mainly because of intra-valley scatter and the space charge field screening on different experimental conditions (different biased electric field and different optical pulse energy).

1. INTRODUCTION

With the development of the ultra-short laser pulse technology, the range applications of photoconductive semiconductor switches (PCSS) become very wide [1–4]. Photoconductive semiconductor switches, holding dc voltage, triggered by femo-second laser pulse are calculated has been used to generate high power THz electromagnetic waves [5–8]. Because of the widespread application of THz electromagnetic waves, the people try to understand the physical mechanism of PCSS generating THz by large numbers of experiment and theoretical analysis to improve the power of THz wave. There have been several groups that investigated into the phenomenon of saturation limiting the power of THz wave generated by single pulse triggering PCSS. To avoid saturation, Liu et al. and Siders et al. demonstrated the generation of THz wave by multi-pulse triggering PCSS. Rodriguez et al. studied the physical mechanism of saturation as a result of the screening effect of radiation field by numerical simulation. To penetrate the physical mechanism of PCSS emitting THz, there is very profound to study THz waveform and the dynamic characteristic of optical-generated carriers which usually rely on strangely the biased electric field and the optical pulse.

In this paper, the dipole characteristic of THz waveforms which was emitted from low-temperature grown GaAs and SI-GaAs photoconductive semiconductor switches on the different experimental conditions are calculated. The results indicate the dipole characteristic of THz waveforms emitted from low-temperature grown GaAs is due to the influence of the lifetime of optical-generated carriers, and we have observed that symmetry of the dipole THz waveforms is more well if the life time is more smaller. To SI-GaAs photoconductive semiconductor switches, the dipole characteristic of THz waveforms is mainly because of different experimental conditions (different biased electric field and different optical pulse energy), the dipole THz waveforms was both happened on the condition that high optical power with low biased voltage or high biased voltage with low optical power triggering PCSS, but in the physical mechanism of the dipole characteristic of THz waveforms, the former differs entirely from the latter on this two different conditions.

2. THEORETICAL CONSIDERATIONS

On the base of Maxwell’s electromagnetic theory, people have qualitatively and quantitatively described the theory of THz radiation produced by optically emitting the photoconductor. The theory accepted in general is the model of current surge [17]. This model persist in THz wave radiated by the photoconductor is formed from the transient surface current which flow in the photoconductor. From the Ohm’s law, we can deduce the equation of surface current:

\[
\vec{J}_s(t) = \sigma_s(t)(\vec{E}_b + \vec{E}_s(t))
\]

where \( \sigma_s(t) \) is time surface electric conductance, \( \vec{E}_b \) is electric field biased the photoconductor. Using the boundary condition of Maxwell equation, the relation of \( \vec{J}_s(t) \) to \( \vec{E}_s(t) \) can be given:

\[
\vec{E}_s(t) = -\frac{\eta_0}{1 + \sqrt{\varepsilon}} \vec{J}_s(t)
\]
Mobility can be given by the following:

\[ \bar{J}_s(t) = -\frac{(1 + \sqrt{\varepsilon})\sigma_s(t)}{\eta_0 \sigma_s(t) + (1 + \sqrt{\varepsilon})} \bar{E}_b \tag{4} \]

From the Equations (3) and (1), we can get the direct relation of surface and the biased electrical field:

\[ \bar{E}_{r}\text{-}\text{far}(t) \approx \frac{1}{A} \frac{d}{dt} \bar{J}_s(t) \tag{5} \]

where \( A \) is the area of the gap between the electrodes, \( z \) is the distance from the radiation center to the observational point. By the means of time domain differential method to the expression (4), the relation of the biased electrical field to the radiation far field of the photoconductor be denoted as:

\[ \bar{E}_{r}\text{-}\text{far}(t) = -\frac{1}{4\pi \varepsilon_0 c^2} \frac{A}{z} \frac{d\sigma_s(t)}{dt} \bar{E}_b \tag{6} \]

Supposing the time domain surface conductance is given by

\[ \sigma_s(t) = \frac{q(1 - R)}{h\nu} \frac{F_{\text{opt}}}{\sqrt{\pi t_{\text{las}}} \nu} \int_{-\infty}^{t} \mu(t, t') \exp \left( -\frac{t - t'}{\tau_c} \right) \exp(-t^2/t_{\text{las}}^2) dt' \tag{7} \]

where, \( q \) is quantity of electricity of electron, \( R \) is the optical reflectance of the PCSS material, \( h\nu \) is the energy of a single photon, \( F_{\text{opt}} \) is the energy of a single laser pulse, \( \tau_c \) is lifetime of the carriers, \( t_{\text{las}} \) is FWHM of optical pulses, \( \mu(t, t') \) is transient mobility. If the biased voltage is lower, the photogenerated carriers can not scatter from the central valley to the satellite valleys, the transient mobility can be given by the following:

\[ \mu(t) = \frac{q \tau_c}{m^*} \left( 1 - \exp \left( -\frac{t}{\tau_s} \right) \right) \tag{8} \]

where \( m^* \) is the valid mass of the electron, \( \tau_s \) is relaxation time.

We can drew a conclusion from these equations: the intension of THz far field radiation is directly affected by the lifetime of carriers in device material, the bias electronic field and activating laser pulse.

3. CALCULATION AND DISCUSSION

3.1. The Relation Between the Lifetime of Carriers and the Dipole Characteristic of THz Waveforms

From the formula (4), (5), (6), (7) and (8), we can calculate the THz waveform radiated by photoconductors with different carrier lifetime. In Figure 1, it shows the different THz waveforms generated by triggering PCSS which semiconductors have four kinds of current carrier lifetime, the PCSS biased at 2 KV/cm electronic field and excited with 800 nm wavelength of light. The typical parameters used in the calculation are: the size of optical spot \( A = 1.0 \times 10^{-6} \text{ m}^2 \); the distance between radiation center and observation point \( z = 1.0 \times 10^{-2} \text{ m} \); the energy of a single pulse \( F = 8.0 \times 10^{-6} \text{ J} \); the FWHM of the laser pulse \( t_{\text{las}} = 100 \text{ fs} \); the photoconductive switches which have different carrier lifetime are three kinds of LT-GaAs (300 fs, 500 fs, 1000 fs) and 100 ps of SI-GaAs. Figure 1(a) shows the THz waveform that radiated by the LT-GaAs whose current carrier lifetime is 300 fs. On the same experimental condition, the amplitude of wave’s positive is minimum, the amplitude of negative is maximal and the waveform is the narrowest, the symmetrical characteristic of dipole is the best; Figure 1(b) is the THz waveform that radiated by LT-GaAs semiconductor with carrier lifetime of 500 fs, the amplitude of positive has increased, at
the same time, the amplitude of negative has decreased, and the waveform is wider, the symmetry is weaker; Figure 1(c) is the THz waveform that radiated by the LT-GaAs semiconductor whose current carrier lifetime is 1000 fs, the amplitude of positive is the highest among the three emitter sources of LT-GaAs, the amplitude of negative is the lowest and the waveform is becoming wider, the symmetry become further weaker; Figure 1(d) is THz waveform that radiated by the LT-GaAs whose current carrier lifetime is 1000 fs, the amplitude of waveform is the highest, the wave has became complete single-pole. From Figure 1, we can draw a conclusion that the current carrier lifetime have important factor on the dipole characteristic and amplitude of the wave, thus the PCSS with shorter lifetime of the current carriers will generate THz wave with better symmetry and smaller amplitude of positive part of dipole THz waveform.

Figure 1: THz waveforms for different photoconductors with different lifetime of carriers and the same experimental.

When laser pulse illuminate on GaAs PCSS surface, a large number of the optical-generated carriers generate rapidly within the period of the laser pulse because of the width of laser pulse less than the lifetime of carriers; at the same time, transient current densities increase rapidly also due to the biased electrical field. This process comes into being the positive part of dipole THz waveform. Subsequently, the processes come into the negative part of dipole THz waveform with the quantity decreasing quickly of the optical-generated carriers. In this process, the carriers nevertheless accelerated continually with the biased electrical field, because the ratio of the decreasing number of optical-generated carriers with time is greater than the ratio of the increasing of current density from accelerating by the bias field, the current densities still present obviously the performance of degradation.

3.2. Influence of Different Experimental Conditions on the Dipole Characteristic of THz Waveforms

The relation of the carriers’ lifetime to the dipole characteristic of THz waveforms was numerically simulated. From the former formulations, we can get the generation of THz pulse by exciting the PCSS which material has longer lifetime carriers such as GaAs et al. has no dipole characteristic. But, the experimental results showed the THz pulse emitted by SI-GaAs has observable characteristic of dipole, even has characteristic of symmetry. In this paper, we present the results of Monte Carlo simulations of the dipole characteristic of THz waveforms generated by simi-insulting GaAs photoconductive switches on different experimental conditions.

3.2.1. The Relation of the Biased Electric Field to the Dipole Characteristic of THz Wave

Figure 2 shows THz waveforms generated at 100 kV/cm biased electric field has oscillation at some degree, while THz waveforms generated at 30 kV/cm, 10 kV/cm biased electric field both have negative part, but at 2 kV/cm, THz waveform entirely demonstrate single-pole characteristic.

Using the single laser pulse wavelength is 800 nm, so it’s energy is 1.55 eV, only 0.12 eV wider than energy gap of SI-GaAs, therefore initial distribution of the carriers is in the central valley. The biased electric field accelerates the optical-generated carriers’ average velocity. Consider higher effective mass and slower drift velocity of the optical-generated holes, so the effect of the optical-
generated holes to THz radiation can be ignored. In PCSS, the photo-generated electrons move to
the electrode and happen to various scatterings. So, the energy of carriers increases from the electric
field and loses energy from scattering. Thereby its energy and momentum present a relaxation.
When the dc bias electric field greater than 4.0 kV/cm (Gunn electric field), a photo-generated
hot electron gain enough energy to transfer from the central valley to two satellite valleys, this
process was defined as non-equivalence inter-valley scattering. Subsequently the electrons in the
satellite valley decrease mobility and velocity rapidly due to its high-effective-mass. The velocity
of a photo-generated hot electron at first increases and secondly decreases at end drive to stable
stage. In the reference paper [19], the alteration process of acceleration of the electrons has been
described. While the dc bias electric field is equal to or greater than 100 kV/cm, the electron’s
velocity increasing and decreasing take on periodic oscillation process. Its periodicity is up to
oscillating central frequency (115 fs) of LO Phonon. This process will cause the oscillating of far-
field THz radiation. The dc bias electric field is higher, the force of it in the electrons is greater,
and consequently, the acceleration is greater also, thus the time current density grows more rapidly.
This case presents that the higher electric field leads to the rise time of THz waveform is shorter
and the peak power of THz waveform is higher. While the electric field is smaller, the energy get
from the electric field is not enough to inter-valley transfer for the electrons. The photo-generated
hot electrons obtain energy from the electric field, meanwhile lose energy under the influence of
polar optical scattering; thereby its energy and momentum present a relaxation phenomena and
drive to stable stage.

The electrons increase continuously in quantity and velocity during the period of the electrons’
acceleration. These appear the rise of THz pulseform. When the rate of increase in quantity
reduces, thus the change rate of current density decrease, this appears the fall of THz pulseform.
As the quantity and velocity of carries is constant, a THz pulse is end.

3.2.2. The Relation of the Light Energy to the Dipole Characteristic of THz Wave
Figure 3 shows far-field THz radiation waveform generated by exciting SI-GaAs semiconductor
with a 30 µm gap and biased at 2 kV/cm electric field. Activating light is laser pulse with 8 µJ
energy, 800 nm wavelength, 100 fs FWHM. Comparing with Figure 2(d), the experimental condition
is totally similar except for laser energy is 10³ greater.

At actual, the difference of laser energy cause the great difference of THz waveform radiated
from the semiconductor surface. In Figure 3, the positive THz radiation has same peak value
with the negative THz radiation, while in Figure 2(d), obviously, THz radiation only has positive
radiation. In a word, only illuminated by high-power laser pulse, far field THz radiation has the
characteristic of dipole.

Actually, not only the switch semiconductor and the bias electric field have influence on THz
wave but also the activating light (its wavelength, width and energy). With respect to SI-GaAs with
the lifetime greater than 100 ps, we analyzed the reason for the dipole characteristic of THz wave
produced by high-power laser pulse triggering SI-GaAs PCSS at low bias electric field and found that the important reason is space charge field screening. In the area of SI-GaAs semiconductor irradiated by optical spot, there are a large number of electron-hole pairs producing in very short time, these electron-hole pairs drift with various velocity towards two electrodes, this case cause the separation of electron and hole, thus form the space charge field contrary to the bias electric field. Therefore, the space charge field acts as a function of screening for the bias electric field. At low electric field, because the space charge field generating from high density carriers can far greater than the bias electric field in some cases, the effect of screening can not be ignored. We can draw a conclusion that it is the space charge field that affects the variation of local carriers’ acceleration. Time-changed current density is reverse, due to the space charge field contrary to the bias electric field, this case forms the negative part of THz wave.

4. CONCLUSIONS
In summary, the conclusion we can drawn that various semiconductor material of PCSS and different experimental condition all affect directly the characteristics of THz wave. The reasons for the dipole characteristic of THz pulse produced by LT-GaAs semiconductor with short lifetime is the carriers’ rapid decrease in very short time, the carriers generate in fs range and recombining in fs level time. While to SI-GaAs semiconductor with long lifetime, the experimental mostly affect the dipole characteristic of THz pulse. When biased at high electric field (to SI-GaAs, greater than Gunn electric field 4.0 kV/cm), inter-valley scattering can happen to the carriers whin the switch semiconductor of III-V group, and its process of acceleration and deceleration finish in fs level time, this case leads to the dipole characteristic of THz wave; When biased at low electric field, the space charge field formed by the high density of carriers can cause the effect of electric field screening, and thus result in the dipole characteristic of THz wave.

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