Intense terahertz radiation from μm-gap GaAs photoconductive antenna

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Abstract. The terahertz pulse energy from photoconductive antenna is mainly derived from that stored in the static bias field. To obtain high intense THz radiation, the distribution of electrical field in semi-insulating GaAs photoconductive antennas was studied at square DC bias voltage. Due to the trap-enhanced space-charge, the electrical field is enhanced at anode and extent to cathode. So the highest effective terahertz radiation is obtained when the laser beam just overlaps the gap. A larger laser beam can reduce the Coulomb screening and radiation screening caused by a focused smaller beam, so the larger beam can increase the efficiency of antenna. At the same electrical field and laser power, an antenna with a larger gap can generate more intensive terahertz radiation than that with a smaller gap.

1. Introduction

The development of terahertz (THz) source is of great importance for a large variety of scientific and technological application [1]. Recently, various methods for generating pulsed THz waves have attracted considerable attention. However, the main methods are photoconductive emitters, surface emitters (such as GaAs, InP, InAs, InSb) [2-6], and electro-optic crystals (optical rectification) [7, 8]. Among these, photoconductive emitters are considered to be the most efficient THz emitters. Various antenna geometries have been used, including Hertzian dipoles, resonant dipole antennas, spiral antennas, stripline antennas, antenna arrays, and so on [9]. Dipolar antennas and stripline dipole antennas are the most common structures.

The shortage of high-power THz sources is the bottleneck of many THz applications. Improving the power of THz waves is important [10]. The radiation mechanism of a photoconductive antenna is attributed to a time-varying current, which results when the photo excited carriers are accelerated across the surface of the photoconductor in the presence of the applied electric field. The terahertz pulse energy is derived from that stored in the static bias field [11]. But the electrical field is not evenly distributed in the electrode gap of antenna [12], so the terahertz amplitude will be different with the laser position [13, 14]. It is important to study the distribution of electrical field in the antenna. The efficiency of antenna also is related to the beam size of antenna. In this paper, we studied...
the different electrical field distribution on stripline semi-insulating (SI) GaAs antennas and optimized the THz generation efficiency of stripline antennas.

2. Experiment
In our experiment, the substrate of antenna is a commercial high-resistivity (>10^7 Ω·cm) liquid-encapsulated-Czochralsky grown, (100)-oriented, SI-GaAs wafer. The width of electrodes is 100 µm, and the gaps between the two electrodes are 50, 100, 150 and 200µm, respectively. The electrode pattern was made using a conventional photolithography technique. Ohmic contacts were obtained by using a standard mixture of Ni/Au-Ge/Au for the metallization and the thickness is 700 nm. Those antennas were tested by a THz time domain spectroscopy (THz-TDS) system. A mode-locked laser based on Er doped fiber oscillator (Femtolite-100 IMRA) was used to generate excitation laser pulses with the center wavelength of 800 nm with the repetition rate of 75 MHz. The width of the pulses was less than 150 fs. The pump beam has a power of 90 mW. The bias power supply provided a square DC voltage, and they were modulated by a lock-in amplifier, the frequency was 75 kHz. Ultrafast switching of the biased emitter by the ultrafast laser generated transient current and produced broadband THz radiation. The THz beam from the emitter was collimated and focused on a 1-mm-thick ZnTe crystal by a pair of off-axis parabolic mirrors. A probe pulse of 10 mW traveled collinear with the THz pulse through the ZnTe crystal. The THz pulse modified the optical refractive index of the probe pulse by means of the linear electro-optic effect and thereby induced an ellipticity of the probe polarization. By measuring this ellipticity as a function of delay with respect to the THz pulse, we can retrieve the time dependence of the electric field of the THz pulse.

3. Distribution of electrical field
To find the laser position dependence of the THz intensity, the laser beam was focused into an about 20 µm spot, the laser spot can illuminate different position of the antenna by precisely adjusting the antenna, and the position of laser spot can be accurately recorded.

Figure 1. Laser position dependence of THz amplitude of SI-GaAs stripline antennas with different gaps biased by square DC voltage.

Figure 1 shows the laser position dependence of the THz amplitude of the 4 antennas biased by the square DC power supply. The THz generation process become more efficient when the excitation is carried out closed to the anode electrodes due to trap-enhanced fields (TEF) in proximity of the anode when the DC bias voltage is used. This TEF results from a number of physical mechanisms including the quasi-static nonlinear field distribution, electron velocity saturation, space charge of uncompensated residual acceptors resulting from the increasing occupancy of deep trap, and field-
enhanced carrier injection [15]. Because the THz intensity is proportional to the bias electrical field [16], the distribution of the laser position dependence of electrical field is same to figure 1. The right edge of the anode was at zero. The maximum THz amplitude locates at the right of zero where the laser spot can entirely illuminate the nearest region close to anode, because the laser spot is not small enough. And in these cases, the electrical fields also distribute in a large region, not are limited in a several microns zone near the anode. This result is in accord with the reference 17. The distribution of electrical field is not like reference 15 reports that up to 90% of the applied potential may exist within 5 µm of the anode, but the considerably intensive electrical field permeated the entire or mostly whole gap.

4. THz generation efficiency

In our experiment, we found the most efficient terahertz radiation generated by SI-GaAs antenna was not obtained by a small focused laser spot. However, when the laser spot with the same power just overlaps the entire gap, the most intensive THz radiation will be generated and the THz amplitude is 3 to 8 times larger than that generated by a small focused spot illuminating the region close to anode, which is shown in figure 2.

![Figure 2](image_url)

**Figure 2.** THz waveforms generated by a 200-µm-gap antenna illuminated by small focused beam (with a 20 µm diameter) and the beam (with a 200 µm diameter) just overlapping the gap.

In this figure, the antenna with 200 µm gap was biased by a square DC voltage with the peak to peak value of 120 V. The THz intensity by a laser spot (with 200 µm diameter) overlapping gap is 3.5 times larger than that from a small focused spot (with 20 µm diameter) with the same power illuminating the region close to anode. This is caused by the screening of photo excited carriers. When the femtosecond laser illuminates the photoconductive antenna, the accelerated photo excited carriers by the bias field will emit THz radiation, but at the same time, as the carriers undergo their spatial dynamics in the bias field, they partially screen out the bias field. The origins of the screening consist of the radiation field and the space-charge (Coulomb) field, which contribute to the collapse of the total electric field acting on the carriers at high carrier density. D. Kim and D. S. Citrin studied the effects of the excitation-spot size and excitation level on the emitted THz radiation by the Monte Carlo method [18]. In the simulation, the laser has a fixed optical power, and the spot size can be changed by focusing optics. In this case, as the excitation-spot size increases, the Coulomb screening decreases rapidly because the distance between the carriers increases due to the decrease of carrier density. In addition, as the carrier density becomes sparse, the carrier numbers contributes the Coulomb and radiation screening field decrease. As a result, the radiation screening field also decreases as the excitation-aperture size increases. Another shortcoming lies in generating THz radiation by small focused spot illumination,
the small focused beam can easily damage the antenna, because the current passes through a narrow passage and the heat caused by current easily damages the material of the narrow passage.

![Figure 3](image1.png)

**Figure 3.** Voltage dependence of the THz intensity of antennas with the exciting laser overlapping the gap.

Then we compared the THz radiation capacity of the four antennas with different gaps. Figure 3 shows the bias voltage dependence of the THz intensity measured for the four antennas with the exciting laser overlapping the gaps. In all cases, the THz intensity linearly increases with the bias voltage and there is no saturation. At the same bias voltage, the antenna with smaller gap can emit a more intensive THz radiation because the electrical field of smaller gap antenna is larger than that of the larger one. Then we investigated the electrical field dependence of the THz intensity signals measured for the four antennas with the exciting laser overlapping the gaps, which is shown in figure 4. At the same electrical field, the THz intensity of larger gap antenna is much higher than the smaller gap antenna. In the test, the THz intensity of 200 µm antenna is more than 4 times larger than that of 50 µm antenna at about 7.5 kV/cm. This is also caused by screening [19]. Large gap antenna can reduce screening because its large gap needs a large laser spot to illuminate, and the distance of photo exciting carriers increase and the density of carriers reduce. So, large gap antennas have high electrical to THz and optical to THz conversion efficiency.

![Figure 4](image2.png)

**Figure 4.** Electrical field dependence of the THz intensity of antennas with the exciting laser overlapping the gap.
5. Conclusions
We have investigated the distribution of electrical field in SI-GaAs stripline antennas biased by a square DC power supply, respectively. And we find the electrical field is increased at anode for DC square bias voltage due to a trap-enhanced space-charge region. But the electrical field is not limited in an about several microns region near anode, considerably intensive electrical field permeates the entire or mostly whole gap. The effective THz radiation is obtained when the laser beam just overlaps the gap, because the larger beam can reduce the Coulomb screening and radiation screening caused by a focused small beam with same power. And at the same electrical field, large gap antenna can generate more intensive THz radiation than small gap antenna also because the large gap antenna can reduce the screening. THz radiation can be improved by using laser beam cover the gap of a large gap antenna.

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7. References
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