Terahertz Emission Properties of Butterfly-shaped Photoconductive Antennas Based on LT-GaAs and SI-GaAs Substrates

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Abstract—Photoconductive antennas (PCA) (one of the most commonly used terahertz emitters) have limited performance (e.g. low output power) and as such, do not fully meet the increasing needs of applications. This work attempts to find a route to further improve the performance of PCA by studying the dependence of emission properties on various parameters. Using substrates of LT-GaAs and SI-GaAs, the responses of PCAs with different structures are studied and compared.

I. INTRODUCTION

A long with the development of terahertz (THz) technology since 1980s, photoconductive antenna (PCA) has been widely used as THz source due to its simple configuration and broadband nature [1]. The representative application of PCA is the THz time-domain spectroscopy (THz-TDS), where PCA is usually used as a pulsed THz emitter and/or receiver [2]. Even though THz-TDS has been proven to be a powerful spectroscopic technique, it is also limited by the fact that the output power of the source is generally too low to measure high-loss samples. This problem stems from the low optical-to-THz conversion efficiency, which is usually much less than 0.1% for a conventional PCA [3]. Therefore, improving the conversion efficiency of a PCA is highly desired in order to enhance the output THz power [4]. Many efforts have been devoted to generally understand the physical mechanism of the PCA based on various structures and substrates [5-11].

In this work, the study of the relationship between the emission properties and various parameters of PCA is further explored by both experiment and numerical simulation.

II. RESULTS

The first focus of this work is on the THz emission properties of PCAs with different substrates. Low-temperature grown GaAs (LT-GaAs) and semi-insulating GaAs (SI-GaAs) substrates are chosen because of their contrasting features. LT-GaAs has an ultra-short carrier lifetime (sub-picosecond) but relatively small mobility. In contrast, SI-GaAs has longer carrier lifetime but much larger mobility. Existing theory predicts that a material with both short carrier lifetime and large mobility would be preferred as a PCA substrate. To analyze the impact of carrier lifetime and mobility, the same PCA structure (butterfly-shaped) on these two substrates are studied at different laser powers and bias voltages in a THz-time-domain-spectroscopy setup. The butterfly-shaped PCAs have a total size of 2 mm by 2 mm. The central gap region is a pair of coplanar lines, with the line length of 100 μm, line width of 5 and 10 μm, and gap size of 34 μm. Two identical PCA structures (with line width of 5 μm) were fabricated on the LT-GaAs and SI-GaAs substrate, respectively. The LT-GaAs based PCA is fabricated by BATOP GmbH and the SI-GaAs based PCA is fabricated in-house. A third PCA with a wider line width (i.e. 10 μm) was also fabricated on the SI-GaAs substrate. The measured THz radiation at various laser powers and DC bias voltages are shown in Fig.1.

Fig. 1. Measured peak output THz temporal pulse of the PCAs at different laser power and bias voltage.

It can be seen that the SI-GaAs based PCA radiates more THz power than the LT-GaAs based PCA at low bias voltage and laser power due to its larger mobility of electrons. However, as the laser power and bias voltage increase, the SI-GaAs based PCA saturates faster and will be ultimately surpassed by the LT-GaAs based PCA. This is a result of stronger screening effect caused by the longer carrier lifetime of SI-GaAs, which leads to the saturation.
Fig. 2. Measured THz radiation emitted by three different PCAs. All of the PCAs have the same butterfly structure as described above. The data are collected at the same laser power (10 mW) and bias voltage (25 V). The red curve represents PCA on LT-GaAs substrate. The blue and green curves represent PCAs on SI-GaAs substrate, respectively. The 5 and 10 μm refer to the line width of the electrodes near the laser excitation spot. The top is the time-domain THz pulse, and the bottom is the corresponding spectrum deduced by FFT.

The performances of SI-GaAs based PCA antennas with different line widths were also experimentally compared. Figure 2 plots the measured THz pulses in time-domain and the corresponding spectra for different substrates and antenna line widths. It is shown that the spectral response of the PCA with 10 μm line width is narrower than that of the PCA with 5 μm line width, which indicates the dependence of the frequency response of the PCA on the dimension of the antenna.

To further understand the physical mechanisms of the THz generation in the PCA, a full-wave numerical model of THz PCA is developed based on FDTD method. This model includes the multi-physical phenomena of the PCA involving the light-matter interaction, photo-excited carrier dynamics and EM propagation of the generated THz radiation. Using this model, the laser power dependence of the PCAs based on LT-GaAs and SI-GaAs substrates is studied, and the results are shown in Fig. 3. The input parameters of the model are listed below. The carrier lifetime of LT-GaAs and SI-GaAs is 0.1 ps and 10 ps, respectively. The mobility of electron of LT-GaAs and SI-GaAs is 600 cm²/Vs and 5000 cm²/Vs, respectively. The laser beam has a diameter of 20 μm and locates near the anode of the PCA. The gap of the PCA is 34 μm, and the line width and length of the antenna is 5 μm and 50 μm, respectively. The simulation region is 50 μm by 44 μm by 2.2 μm in total.

Fig. 3. Simulation results of the parameter study of LT-GaAs and SI-GaAs based PCAs. The dependence of the peak of THz pulse on the laser power is simulated at two specific bias voltages (i.e. 5V and 20V), for both LT-GaAs and SI-GaAs based PCAs.

The saturation characteristic of the LT-GaAs and SI-GaAs based PCAs can be clearly observed in Fig. 3. Moreover, as observed in experiment, the simulation result shows that LT-GaAs based PCA will have better performance at higher laser power. Therefore, the simulation results share qualitatively similar features with the experimental data. Further improvement of the numerical model to quantitatively predict the PCA performance is under way.

III. DISCUSSION AND CONCLUSION

In summary, the performance of the butterfly-shaped PCA with regard to various parameters was studied by experimental and numerical method. Improved performance can be expected by optimizing these parameters comprehensively. For example, the THz radiation of PCA has nearly linear dependence on the bias voltage. In other words, for the same input optical power, the output THz power can be increased along with the bias field. It is a straightforward way to improve the optics-to-THz efficiency by biasing the PCA with as high voltage as possible. However, the highest bias field is limited by the breakdown of the substrate. In addition, the low optics-to-THz efficiency is mainly caused by the low quantum efficiency, in which most of the photo-excited carriers do not contribute to THz radiation but thermal noise. It is a promising way to break the bottleneck by improving the quantum efficiency.

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