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Jitao Zhang
Mingguang Tuo
Min Liang
Hao Xin

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Detection properties of photoconductive antennas fabricated on low-temperature-grown GaAs and ErAs: GaAs at subterahertz band

Jitao Zhang,[a,b,*] **Mingguang Tuo,**[a] **Min Liang,**[a] **and Hao Xin**[a,*]
[a]University of Arizona, Department of Electrical and Computer Engineering, Tucson, Arizona, United States
[b]University of Maryland, Fischell Department of Bioengineering, College Park, Maryland, United States

Abstract. Terahertz (THz) spectroscopy with high sensitivity is essential for biological application considering the strong absorption and scattering effects therein. As the most commonly used THz detector, the photoconductive antenna's (PCA) response greatly relies on the properties of the substrate's material. THz detection properties of the PCAs fabricated on low-temperature-grown GaAs (LT-GaAs) and ErAs:GaAs superlattices were compared at the sub-THz band. The detection efficiency of the PCAs with regard to incident laser power was characterized. In addition, using the PCAs as detectors, the signal-to-noise ratio (SNR) and dynamic range (DR) of a terahertz time-domain spectroscopy were quantified. The result indicates that the PCA detector with LT-GaAs has higher efficiency than the one with ErAs:GaAs. Consequently, the corresponding THz spectrometer has better SNR and DR. This result is contrary to the previous report, in which enhanced detection efficiency was observed with ErAs:GaAs-based PCA, which is probably due to the different structures of ErAs:GaAs superlattices used in the experiment. [DOI: 10.1117/1.OE.59.6.061619]

Keywords: terahertz; photoconductive antenna; detection; low-temperature-grown GaAs; ErAs.

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1 Introduction

Terahertz time-domain spectroscopy (THz-TDS) is a powerful tool in vast application ranging from material characterization, spectral fingerprint identification, biophotonics, and nondestructive inspection.[1–3] The photoconductive antennas (PCAs) are widely used as both THz source and detector in the THz-TDS system. As a consequence, the performance of the spectrometer is tightly related to the emission and detection properties of the PCAs. The PCA detector, gated by a femtosecond laser pulse, retrieves the incident THz pulse waveform by producing output current that is proportional to the amplitude of the incoming THz field. Apart from the antenna structure, the response of a PCA detector is mainly determined by the photoconductive materials on which it is fabricated. One of the most used materials is low-temperature-grown GaAs (LT-GaAs). Other materials, such as silicon-on-sapphire, semi-insulating GaAs (SI-GaAs), InP, and quantum dot-based devices,[4–7] were also used for THz detection.[8–11] In addition, superlattices based on GaAs and InGa(Al)As were proposed as potential materials for THz PCAs, such as InGaAs:Be^{2+}/InAlAs, LT-GaAs/GaAs:Si, ErSb/GaSb, and LuAs/GaAs.[12–15] Unlike bulk material, the superlattices consist of a periodically alternating structure of two (or more) materials, which allows highly flexible adjustment of the electro-optic properties by tuning the growth parameters and geometric structures. Therefore, the THz devices based on superlattices are expected to be the promising alternatives of the bulk materials.[16]

Recently, a new superlattice, self-assembled ErAs nanoislands embedded in a GaAs (ErAs:GaAs), attracted lots of interest in the THz community.[16–22] It is composed of equidistant layers

*Address all correspondence to Jitao Zhang jtzhang4@umd.edu; Hao Xin hxin@email.arizona.edu

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of ErAs monolayers incorporated in a high-quality GaAs matrix by molecular beam epitaxy. The ErAs layers act as trapping sites whose capture time can be as low as 190 fs, making it an ideal layer for ultrafast transduction. By adjusting the distance between the adjacent ErAs layer, research has demonstrated that the response can be tuned by two-order of magnitudes.[16] In addition, the dark resistance and trap density can be accessed independently by tuning the island size and density, which are controlled by the growth temperature and the deposit amount. Initially, the ErAs:GaAs was applied to THz generation by PCA and photomixer. Recently, researchers began to use it as THz PCA detector and demonstrated strong enhancement in THz detection efficiency when comparing with homemade LT-GaAs.[23] The enhancement was attributed to the increased mobility of ErAs:GaAs.

An ideal THz PCA detector should feature a broad bandwidth, an efficient response as well as a low noise, which are tightly related to the material properties (such as carrier lifetime and mobility) of the active layer. LT-GaAs is widely used in the PCA detector as it has sub-picosecond lifetime and high mobility. Comparing with LT-GaAs, the ErAs:GaAs not only features short carrier lifetime but also provides additional advantages of greater flexibility and control of carrier lifetime and mobility, making it a promising alternative material for the THz PCA detector.

In this work, the detection properties of a butterfly-shaped PCA fabricated on ErAs:GaAs were compared with that of a commercial one fabricated on LT-GaAs. The detection efficiency with regard to the incident laser power was measured and compared at the same condition via a THz-TDS system, and the corresponding signal-to-noise ratio (SNR) and dynamic range (DR) of the THz-TDS was characterized when using each PCAs as the detector. The results indicate that the detection efficiency of the LT-GaAs-based PCA outperforms that of the ErAs:GaAs-based one. Consequently, the SNR and DR of THz-TDS were higher when using the LT-GaAs-based PCA as a detector. Our result is contrast to the previous report in which a strongly enhanced detection efficiency with ErAs:GaAs-based PCA was observed.[23] As the material properties of ErAs:GaAs tightly depend on the superlatttice's structure,[16] the different structure of the ErAs: GaAs used in the experiment possibly accounts for the discrepancy.

2 Experiment

Figure 1(a) shows the metallic structure fabricated on both the LT-GaAs and ErAs:GaAs substrates. The metallic structure was made of 20-nm Cr/150-nm Au by standard photolithography and lift-off techniques. The butterfly-shaped antenna was used because it has good radiation properties at sub-THz ban.[24] The central region has a dipole structure with bias line. The length and width of the dipole are 34 and 10 μm, respectively. The gap for a laser illumination is 6 μm. The length and width of the bias line are 100 and 5 μm, respectively. As shown in Fig. 1(b), the LT-GaAs-based PCA is a commercial one (PCA-44-06-10-800-h, BATOP) that fabricated on a 625-μm SI-GaAs substrate with 2-μm LT-GaAs epilayer on top and 0.2-μm AlAs in between, which serves as a wide-bandgap barrier between the LT-GaAs layer and the wafer material and

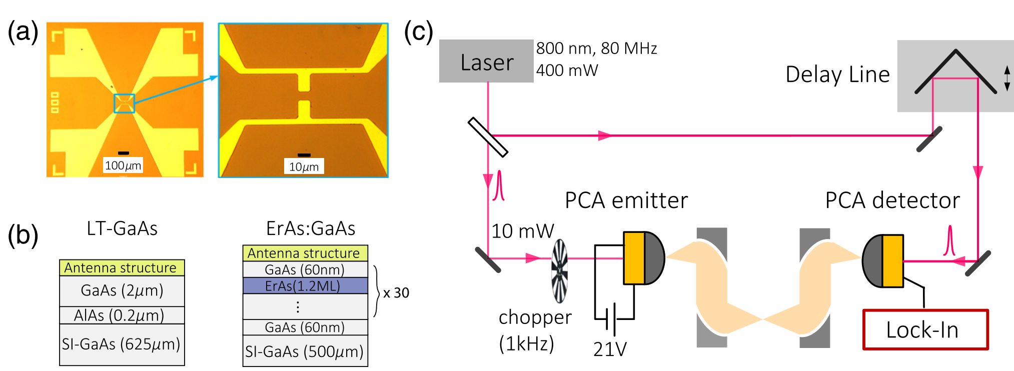

Fig. 1 (a) Dimension of the butterfly-shaped PCA structure. (b) Structures of LT-GaAs and ErAs:GaAs substrates. ML, monolayer. (c) Schematic of the THz-TDS setup.

is a good heat spreader. The commercial PCA detector was selected because it is easily accessible for researchers worldwide and can serve as a benchmark. The ErAs superlattice layer was grown on 500-μm SI-GaAs at 490°C by molecular beam epitaxy and consisted of 30 superlattice periods each containing 1.2 monolayer of ErAs islands and 60 nm GaAs. The carrier lifetime was characterized as 0.88 ps by pump-probe measurement at 820 nm. The thickness of GaAs and the periodic number were decided in consideration of the effective absorption of laser beam as well as the efficient generation of the photoexcited current.

The measurement was accomplished by a home-built THz-TDS system, as shown in Fig. 1(c). A Ti:sapphire femtosecond laser (Micra 5, Coherent Inc.) with center wavelength of 800 nm and repetition rate of 80 MHz was used as the light source. The maximum output power was about 400 mW, and the pulse width was 45 fs. A LT-GaAs-based PCA emitter (PCA-44-34-100-800-h, BATOP) was used as THz source, which worked at bias of 21 V and laser power of 10 mW. The gated laser covered the whole gap region of the PCA detector, which is about 6 μm in diameter. During measurement, both the PCA emitter and detector were attached on the hyperhemispherical silicon lens ($f = 26.5$ mm) to improve the signal strength. The generated THz signal was guided by a group of parabolic mirrors and coupled into the detector. As the focal length of the silicon lens is much larger than the chip thickness, the effect of thickness difference between two PCA substrates can be ignored. To make sure both PCA detectors are illuminated by the identical laser intensity, the PCA detector was placed on a precise three-dimensional stage and aligned to the focused beam spot by monitoring the photoexcited resistance. The pump beam of the emitter was modulated at 1 kHz by an optical chopper, and the output signal of the PCA detector was collected by a lock-in amplifier with a time constant of 30 ms. With the same THz source, the response of each detector was measured regarding the incident laser power. In addition, the SNR and DR of a THz-TDS system were evaluated when using each PCA as a detector.

3 Results and Discussion

Figure 2 shows the detected THz signal in time- and frequency-domains by the PCA detectors. The gated laser power was 5.8 mW. The detected spectrum mainly lies in sub-THz band that is determined by the PCA emitter used in the experiment. It indicates that LT-GaAs-based PCA has stronger THz response than ErAs:GaAs-based one. For a further investigation, the gated laser

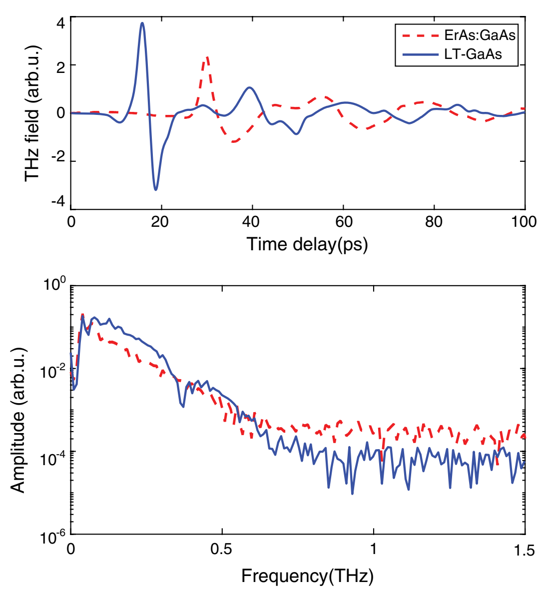

Fig. 2 Time- and frequency-domain THz signal detected by ErAs:GaAs- and LT-GaAs-based PCA detectors. The time-domain data of ErAs:GaAs detector were arbitrarily shifted on horizontal axis for demonstration purpose. The spectral data are calculated from time-domain THz pulse by fast Fourier transform. arb.u., arbitrary unit.

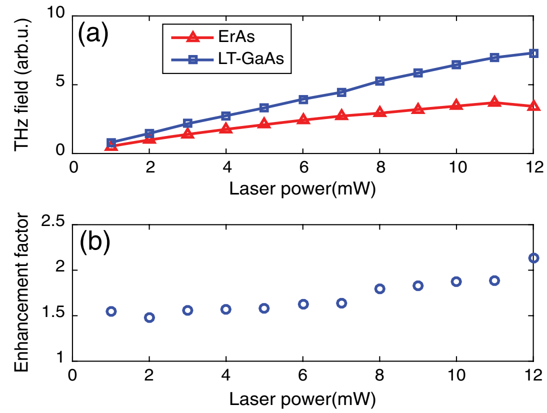

Fig. 3 Comparison of detection efficiency of ErAs:GaAs- and LT-GaAs-based PCAs. (a) Dependence of the detected THz signal on the gated laser power and (b) corresponding enhancement factor. The triangle and circular represent measured data, and the solid lines are the guides of eye. arb.u., arbitrary unit.

power of the detector was varied from 1 to 12 mW with 1-mW increment, and the corresponding detected signal is shown in Fig. 3.

According to Fig. 3, the detecting efficiency of the LT-GaAs-based PCA is always better than that of the ErAs:GaAs-based one. At low laser power, both detectors showed linear dependence. However, the saturation effect could be clearly seen at high laser power. This effect was more severe for the ErAs:GaAs-based PCA, where the detected signal starts to decrease when the laser power was increased from 11 to 12 mW. Moreover, the enhancement factor in Fig. 3(b) indicates that the ErAs:GaAs-based PCA saturates earlier against the gated laser power, and the THz field detection efficiency of the LT-GaAs-based PCA can be as large as two times of that of the ErAs:GaAs-based one when the gated laser power was 12 mW. The saturation effect of PCAs has been reported before,[10,23] and it can be attributed to the screening effect of the free space charges when the excited carriers have long lifetime and large mobility.[25,26] In this work, the carrier lifetime of ErAs:GaAs is in subpicosecond and similar to that of LT-GaAs, indicating that the screening effect is hardly built with current low pump power. Instead, the low concentration of trapping sites in the active layer could be the possible reason.[23] Further investigation of the saturation mechanism in ErAs:GaAs would be intriguing.

Figures 4 and 5 show the corresponding SNRs and DRs of a THz-TDS system when using the ErAs:GaAs- and LT-GaAs-based PCAs as detectors. The gated laser power of the detector was fixed at 5.8 mW. In Fig. 6, the noise floor was obtained when the DC voltage of the emitter was turned off. The time trace data were then converted into frequency domain by performing fast Fourier transform. Each measurement was repeated three times, and the mean value and

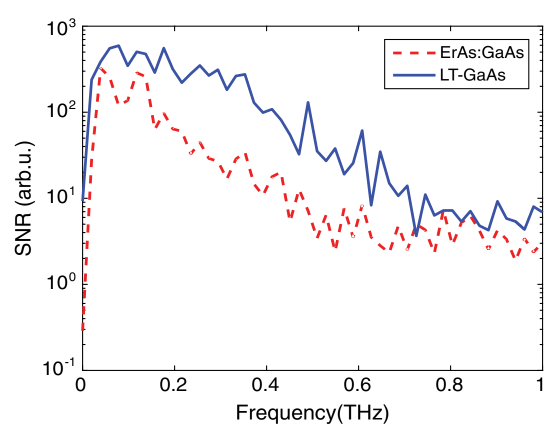

Fig. 4 Comparison of the SNR of THz-TDS system when using ErAs:GaAs-based PCA and LT-GaAs-based PCA as detectors. arb.u., arbitrary unit.

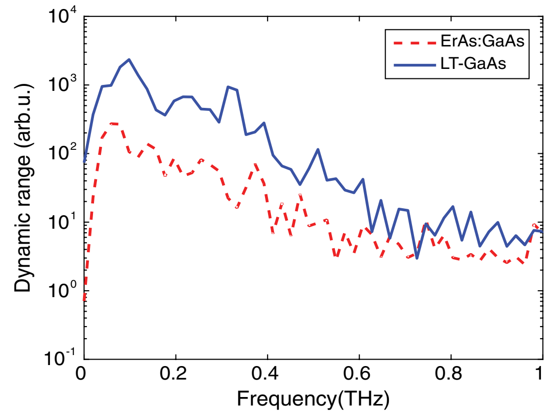

Fig. 5 Comparison of the DR of THz-TDS system when using ErAs:GaAs-based PCA and LT-GaAs-based PCA as detectors. arb.u., arbitrary unit.

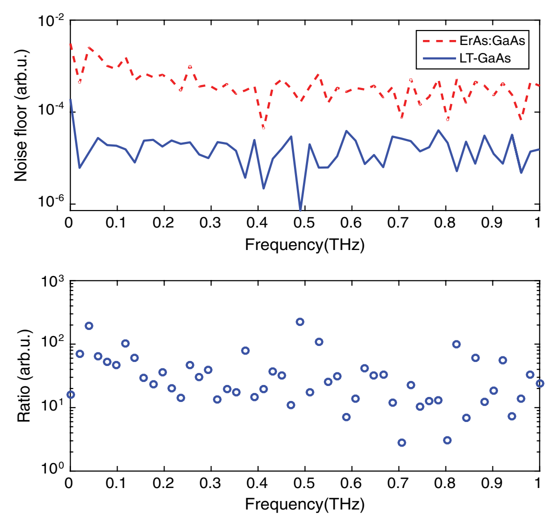

Fig. 6 Comparison of the noise floor of THz-TDS system when using ErAs:GaAs-based PCA and LT-GaAs-based PCA as detectors. The ratio is calculated by dividing ErAs:GaAs's data with LT-GaAs's data. arb.u., arbitrary unit.

standard deviation of the THz field in frequency domain were calculated, and the SNR and DR were quantified based on the definition:[27]

$$\mathrm{SNR} = \frac{E_{\mathrm{mean}}}{E_{\mathrm{SD}}}, \quad \mathrm{DR} = \frac{E_{\mathrm{mean}}}{N_{\mathrm{RMS}}}, \tag{1}$$

where E_{mean} and E_{SD} are mean and standard deviation of the measured signal, respectively. N_{RMS} is the root-mean-square of the noise floor. According to Figs. 4 and 5, the LT-GaAs-based detector shows better SNR and DR for the THz-TDS system. It stems from the fact that LT-GaAs-based PCA has not only higher detection efficiency (as shown in Fig. 3) but also smaller noise floor (as shown in Fig. 6) than the ErAs:GaAs-based PCA, and the latter is much more emphasized because the noise floor of ErAs:GaAs varies between 10 and 100 times of that of LT-GaAs within the observed spectrum. The longer carrier lifetime of the ErAs:GaAs is probably responsible for the higher noise, as more carriers can flow to the electrode before recombination and thus generate larger dark current.

The enhanced detection efficiency of PCA detector fabricated on ErAs:GaAs has previously been reported,[23] where the superlattice period contains 25 nm of GaAs and 1.2 monolayer of ErAs. Because the photoexcited carriers are generated in the GaAs layer and recombine in the nanoislands or defects in ErAs layer, the different period thickness has strong effect on the magnitude and response time of the PCA detector.[16,18] In our experiment, the GaAs layer (60 nm) is 2.5 times thicker than found in the literature. Thus, longer time is required for the carriers to reach the ErAs layer before recombination, which ultimately results in less efficient response of the PCA detector due to the limited lifetime of the carriers. This also suggests the challenge of using ErAs:GaAs as the active layer of the THz PCA detector: since multiple growth parameters and structures can affect the material properties, the performance of the PCA detector may vary dramatically depending on specific design. As a future work, the comparison between substrates having different period thickness will provide direct evidence. For a PCA detector fabricated on bulk active layer, longer carrier lifetime might result in higher responsivity,[10,28] which, however, is not the case for ErAs:GaAs here. As the generation and recombination of the photoexcited carriers were accomplished at different layers, the limited trapping sites in ErAs layer and the thickness of the GaAs layer could be obstacles of the effective response.

In general, the DR and SNR of our THz-TDS system are not high. Several noise sources may have contributions, such as laser intensity fluctuation, electronic and optical noise, and jitter noise from the delay line.[27,29–31] Among them, the electronic noise and jitter noise have significant contribution to the noise floor. The electronic noise is mainly from the PCA detection and data acquisition module, and the jitter noise is due to the mechanical variation of the stepwise translational stage and the refractive index fluctuation of air within the delay line. In addition, the SNR is also affected by the noise from the PCA emitter that is mostly attributed to the laser intensity fluctuation. However, these noise sources have similar contribution to both PCA detectors as the devices were tested under the same condition.

4 Conclusion

The THz detection properties of the PCAs fabricated on substrates of ErAs:GaAs and LT-GaAs were measured and compared via a THz-TDS system at sub-THz band. The results indicate that the LT-GaAs-based PCA has higher THz detection efficiency as well as lower noise floor, which makes the THz-TDS has better performance when using LT-GaAs-based PCA as detector. Our result is contrary to the previous report in which a strong enhancement in ErAs:GaAs-based detector was observed. As the material properties of ErAs:GaAs is strongly related to the superlattice's structure, the discrepancy is possibly caused by the different structures (such as the single layer thickness and the overall periods) of the ErAs:GaAs material used in the experiment.

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Jitao Zhang received his BS degree in optical science and information from Wuhan University, Wuhan, China, in 2006, and his PhD in optical engineering from Tsinghua University, Beijing, China, in 2010. He was a postdoctoral researcher in the University of Arizona from 2012 to 2014 and is currently an assistant research professor in the Fischell Department of Bioengineering at the University of Maryland, College Park, USA.

Mingguang Tuo received his BS and MS degrees in electrical engineering from Xidian University, Xi'an, China, in 2006 and 2009, respectively. He received his PhD in electrical and computer engineering from the University of Arizona, Tuscon, Arizona, USA, in 2018. He is now a senior engineer at Qualcomm.

Min Liang received his BS and MS degrees in electronic science and engineering from Nanjing University, Nanjing, China, 2007 and 2010, respectively. He received his PhD in the Electrical and Computer Engineering Department, University of Arizona, Tucson, Arizona, USA, in 2016. He is currently a postdoctoral researcher in the Department of Electrical and Computer Engineering at the University of Arizona.

Hao Xin received his PhD in physics from Massachusetts Institute of Technology, Cambridge, Massachusetts, USA, in 2001. Currently, he is a professor and director of the Cognitive Sensing Center in the Electrical and Computer Engineering Department and Physics Department at the University of Arizona, Tucson, Arizona, USA.