# Optimization of wide band mesa-type enhanced terahertz photoconductive antenna at 1550 nm*

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A mesa-type enhanced InGaAs/InAlAs multilayer heterostructure (MLHS) terahertz photoconductive antenna (PCA) at 1550 nm is demonstrated on an InP substrate. The InGaAs/InAlAs superlattice multilayer heterostructures are grown and studied with different temperatures and thickness ratios of InGaAs/InAlAs. The PCAs with different gap sizes and pad sizes are fabricated and characterized. The PCAs are evaluated as THz emitters in a THz time domain spectrometer and we measure the optimized THz bandwidth in excess of 2 THz.

**Keywords:** THz, InGaAs/InAlAs MLHS, photoconductive antenna

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## 1. Introduction

Terahertz time domain spectroscopy (THz TDS) has become one of the most promising methods for industrial inspection and scientific analysis, with the constant research into the terahertz technology.[1] The state-of-the-art TDS system typically deploys low temperature molecular beam epitaxy (MBE) grown GaAs photoconductive antennas (PCAs) and bulky Ti:sapphire femtosecond laser at 800 nm. The core part, GaAs PCAs, has been studied in the last two decades. Various progress in aspects such as incorporating plasmonic contact electrodes,[2] and avalanche multiplication[3] has been made to further improve the output power of GaAs PCAs. But the disadvantages of the current system are heavy, expensive and the use of free space optics, which is mainly due to the femtosecond laser. We suggest that the THz TDS system should be compact, user-friendly, all-fiber based and cost effective to more applications. Numerous attempts have been made to make use of the mature Er-doped femtosecond fiber lasers at 1550-nm wavelength, which corresponds to InGaAs based photoconductive antennas.[4–9] However, great potential remains for further development to improve the PCA output power and efficiency. In recent years InGaAs/InAlAs multilayer heterostructure (MLHS) grown by MBE has been proved to have high optical conversion efficiency, low noise level and rather broad THz band emission. At the growth temperature of approx. 400 °C, the residual carrier concentration is still on the order of $10^{16}$ cm$^{-3}$, which is the minimum of defect incorporation.[10] Meanwhile, due to the thermodynamics in the MBE growth process, the InAlAs layer shows increased defect incorporation, which means more carrier traps.[11] Using the above characteristics, we fabricate 1550-nm laser excited InGaAs/InAlAs MLHS photoconductive antennas and investigate the influences of growth temperature, thickness ratio of the InGaAs/InAlAs substrate, as well as the gap size and pad size of the antenna on the characteristics of the THz emission.

## 2. Experimental methods

### 2.1. Materials characterizations

Our device was grown on the Gen 930 MBE system. We designed 100 pairs of $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ MLHS on the InP lattice-matched substrates. To investigate the influences of growth temperature and thickness ratio on the emission of THz wave, two groups of samples were made as follows: group one (G1) was grown at different growth temperatures, ranging from 160 °C to 460 °C in steps of 100 °C; group two (G2) contained different InGaAs/InAlAs thickness ratios, in which the thickness of InGaAs was 12 nm and the thickness values of InAlAs were 1 nm, 2 nm, 4 nm, and 8 nm, respectively. The above data are shown in Table 1.

**Table 1.** Samples with respective growth parameters.

| Sample | Temperature/°C | Sample | The thickness of InAlAs/nm |
|---|---|---|---|
| G1-1 | 160 | G2-1 | 1 |
| G1-2 | 260 | G2-2 | 2 |
| G1-3 | 360 | G2-3 | 4 |
| G1-4 | 460 | G2-4 | 8 |

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### 2.2. Device fabrication

Next, we fabricated the THz PCA devices. We designed the dipole-sized antenna with two stripe lines beside the InGaAs/InAlAs MLHS layers.[12] To minimize the dark current through the MLHS, one mesa was patterned and wet-etched on the epitaxy layer as shown in Fig. 1. To investigate the influences of gap size and pad size on the emission of PCAs, two groups of samples were made as follows: group three (G3) had different gap sizes of 25 μm×40 μm, 50 μm×40 μm, 80 μm×40 μm, and 100 μm×40 μm; group four (G4) had different pad sizes of 250 μm×250 μm, 350 μm×350 μm, 500 μm×500 μm, and 1955 μm×750 μm. The above is shown in Table 2. The stripe lines and pads were metallized by using magnetron sputtering with Ti (50 nm) and Au (300 nm). The width of the stripe lines besides the mesa was 20 μm for each of all THz PCAs.

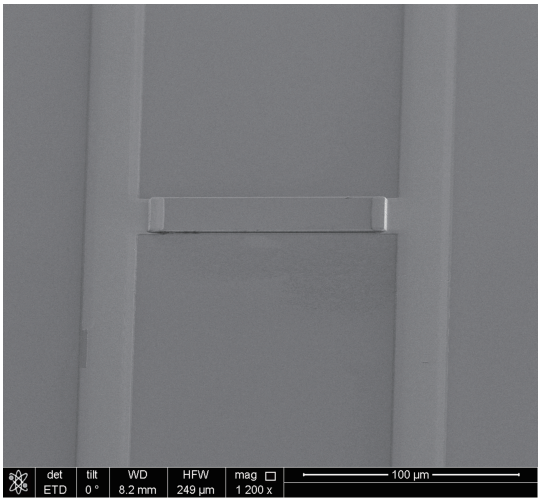



**Fig. 1.** SEM image of fabricated THz PCA dipole.

**Table 2.** Samples with different fabrication parameters.

| Sample | Gap size/μm$^2$ | Sample | Pad size/μm$^2$ |
|---|---|---|---|
| G3-1 | 25×40 | G4-1 | 250×250 |
| G3-2 | 50×40 | G4-2 | 350×350 |
| G3-3 | 80×40 | G4-3 | 500×500 |
| G3-4 | 100×40 | G4-4 | 1955×750 |

## 3. Results and discussion

Our PCAs are evaluated in the time domain spectroscopy (TDS) test. One pre-compensated pulsed Er-doped fiber laser with a repetition rate of 100 MHz is used to pump and probe beams separately. The pulse of the laser is less than full width at half maximum of 100 fs. The pump beam is focused on the PCA mesa area and the probe beam on another prepared detector. The PCAs we used are as mentioned above, while the detector is a Menlo commercial Be-doped InGaAs/InAlAs MLHS photoconductive receiver antenna. Both PCAs and detector are attached to a hyper-hemispherical silicon lens on the backside and off-axis parabolic mirrors are used in the light path to focus the THz emission onto the detector. We also place a mechanical delay stage on the path of the probe laser beam to introduce a time delay. A biased voltage modulated at 20 V is applied to the PCAs. The optical excitation powers at the PCA and the detector are both 15 mW.

### 3.1. Temperature dependence of THz emission

To investigate the influence of the MBE growth, two groups (G1 and G2) are kept at the same gap size and pad size. Group one (G1) grows at different growth temperatures from 160 °C to 460 °C in steps of 100 °C. Choosing this range of temperatures is mainly because 460 °C is commonly regarded as the suitable temperature for crystal quality, while lower temperature usually increases the defects in the InGaAs layer.[13,14] The defect is $As_{Ga}$ related and the decay time is about several tens of picoseconds.[15] As can be seen in Figs. 2(a) and 2(b), PCA grown at 460 °C exhibits the highest THz emission and the broadband is over 2 THz. We have also prepared another commercial PCA claimed to be

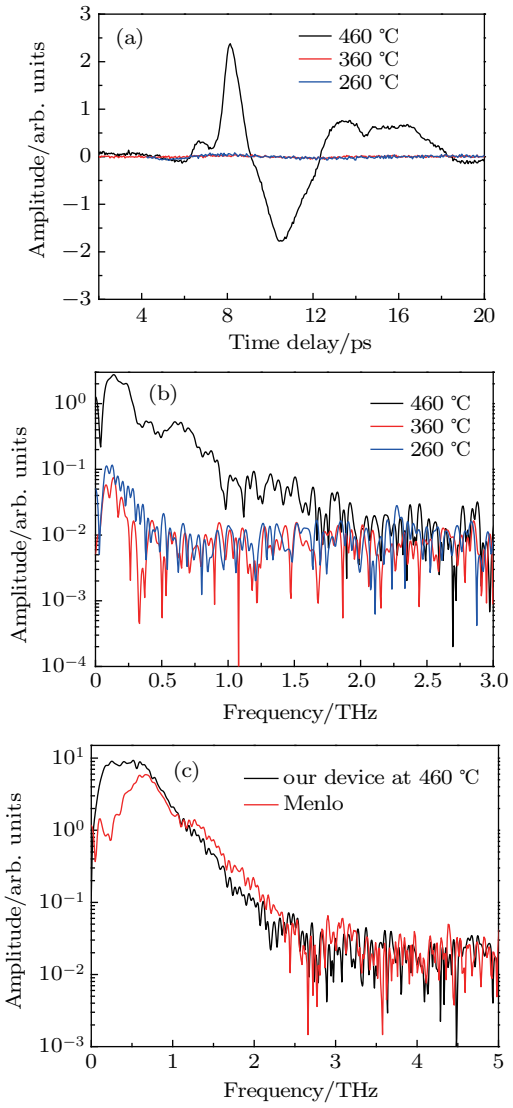



**Fig. 2.** (color online) Amplitudes versus (a) time delay and ((b) and (c)) frequency at different temperatures of our device.

over 3 THz to be placed in the same system. The purpose of placing one reference PCA is to eliminate the system difference when comparing two PCAs. It can be seen from Fig. 2(c) that the spectral bandwidth of PCA at 460 °C is comparable to the bandwidth obtained from the reference PCA, both extending over 2 THz. The broad bandwidth suggests that the InGaAs layer contains a fast carrier trap. While the device grown at 460 °C proves to have high performance, other PCAs grown at lower temperature exhibit rather low THz emission. We are not able to collect the data from the sample at 160 °C because the signal is at the same level of noise. We suggest the temperature for InAlAs is too low to form monocrystal. This quality cannot provide enough high resistance to emit a THz wave.

### 3.2. Thickness ratio dependence of THz emission

In the other group, group 2 (G2) is used to investigate the influences of the ratio of the thickness of InGaAs and InAlAs layer. While the thickness of the InGaAs layer is kept at 12 nm, the thickness values of InAlAs are 1 nm, 2 nm, 4 nm, and 8 nm, respectively. All samples are grown at 460 °C, consisting of 100 periods. The THz-TDS spectra of the four samples show difference in time domain and it can be explained as follows: different InAlAs thickness values lead to different resistances and different penetrations of pump laser. However, no significant difference in frequency domain can be seen from Fig. 3(b). This suggests that the main recombination process is in the InGaAs layer and independent of the InAlAs thickness, which is in agreement with the results obtained by Dietz *et al.*[16]

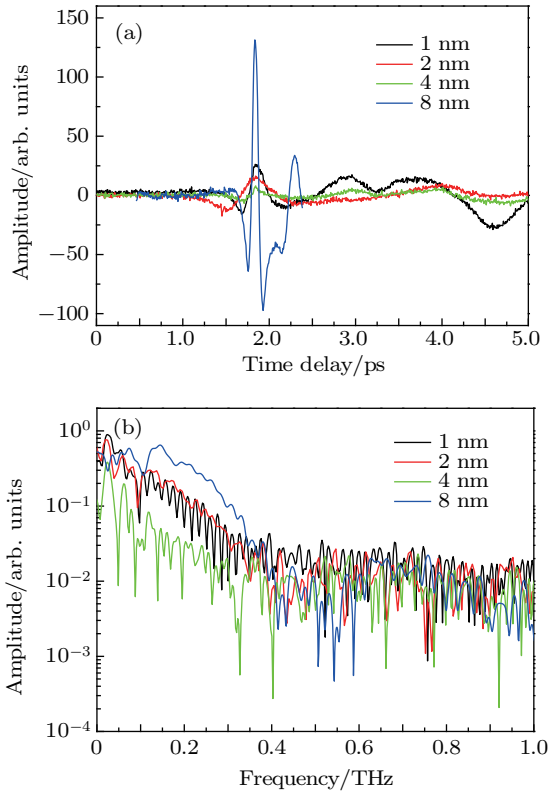



**Fig. 3.** (color online) Variations of amplitudes versus (a) time delay and (b) frequency.

### 3.3. Gap size dependence of THz emission

Beside the growth process, the patterns of gap and pad also influence the emission of THz wave. First, we consider four different gap sizes: 25 μm, 50 μm, 80 μm, and 100 μm. We assume that the main concern of the gap size is the balance between biased voltage and the laser spot size. If the gap is wide, enough biased voltage should be used to guarantee that the photo-induced carrier reaches the electrode fast to emit a THz wave.[17] If the gap is narrow, the difficulty appears in the minimization of the laser spot. The diameters of laser spots focusing on the PCA and detector are both less than 100 μm, which is less than the widest gap of the prepared device. It can be seen from Fig. 4(a) that in this group, gap 25 μm generates more powers of THz emission than the others. As the gap size becomes wider, the output power and efficiency of optical conversion gradually decreases. It validates the assumption that there is a balance between the voltage and spot size. However, when the spot is smaller than the gap, the biased voltage dominates. Narrow gap size can be considered as a priority when designing the PCAs.

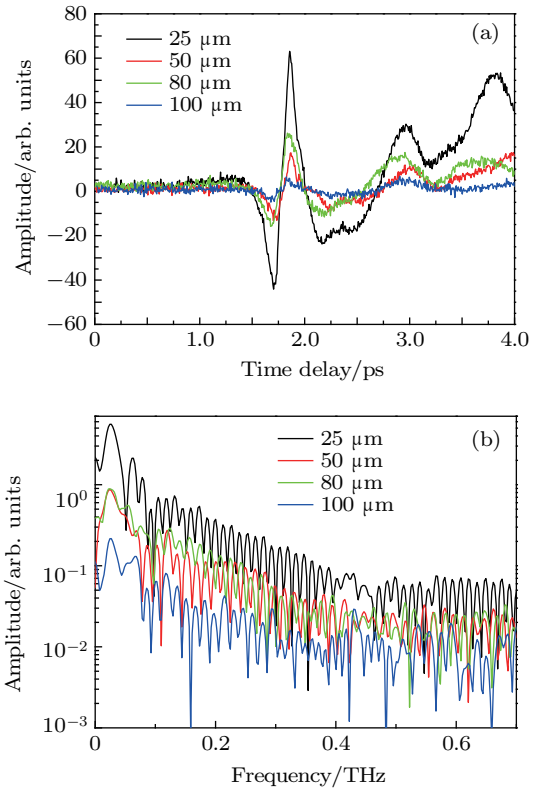



**Fig. 4.** (color online) Amplitudes versus (a) time delay and (b) frequency for the devices with different gap sizes.

### 3.4. Bonding pad size dependence of THz emission

Another important factor is the size of bonding pad. We fabricate four pads with different sizes (250 μm×250 μm,

350 μm×350 μm, 500 μm×500 μm, and 1955 μm×750 μm). It is assumed that because the wavelength of the generated THz wave is in the range of a millimeter, which is comparable to the size of the pad, the emitted electromagnet wave will be influenced. In our experiment, it can be seen from Fig. 5 that the pad size of 250 μm×250 μm presents the optimal parameter. The amplitude is highest which means that the power is highest and the bandwidth is beyond 2 THz. The inset indicates that the FWHMs are in a range of 1 ps and the bandwidths in the frequency domain are in the same range of about 1 THz. We suggest that different pad sizes change the efficiency of the emitted THz wave. When the frequency is 1 THz, the wavelength is 300 μm. The pad size is in the same range of the bandwidth, so the interaction between the pad and the wave changes the power and bandwidth of the THz wave. It can be explained according to the theory of antenna. The result of the experiment is consistent with the assumption that the wavelength of THz matters. We suggest that the size of the pad should be carefully designed to guarantee the optimized THz wave.

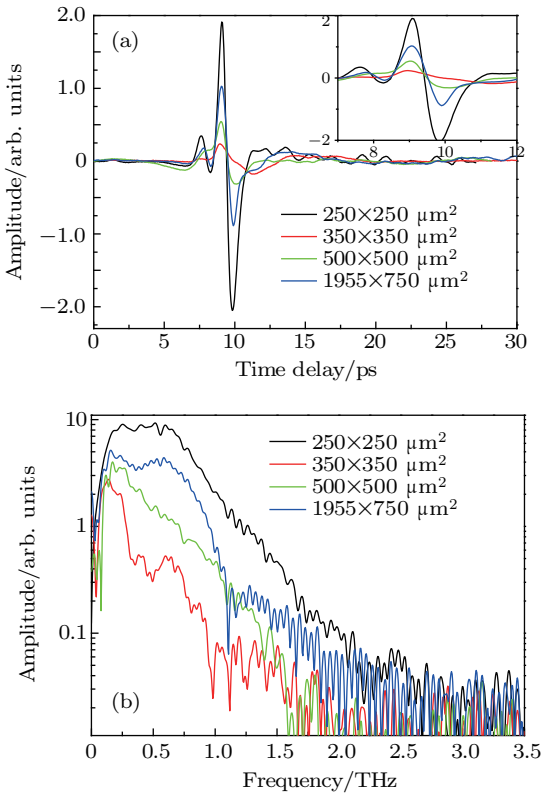



**Fig. 5.** (color online) Amplitudes versus (a) time delay and (b) frequency for the devices with different bonding pad sizes.

## 4. Conclusions and perspectives

In this work, a mesa-type enhanced InGaAs/InAlAs MLHS PCA is fabricated in a standard process. Then we investigate the influences of growth temperature, thickness ratio of the InGaAs/InAlAs substrate, as well as the gap size and pad size of the antenna on the characteristics of the THz emission. By exploiting its high mobility and dark resistance, an InGaAs/InAlAs PCA with optimized output power and more than 2-THz bandwidth is obtained. Further optimizing the PCA excited at 1550 nm should start with high temperature, narrow gap and small pad size. The THz spectrum extending more than 2 THz is conducive to portable and handheld THz TDS systems.

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