Ultrabroadband terahertz field detection by proton-bombarded InP photoconductive antennas

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Abstract: Photoconductive (PC) antennas fabricated on InP bombarded with 180 keV protons of different dosages ($InP:H^+$) all exhibit a useful bandwidth of about 30 THz, comparable to that of the LT-GaAs PC antenna. The peak signal current of the best InP: H^+ device (dosage of 10^{15} ions/cm^2) is slightly higher than that of the LT-GaAs one, while the signal-to-noise ratio (SNR) of the former is about half of that of the latter due to lower resistivity. This suggests that InP: H^+ can be a good substrate for THz PC antennas with proper annealing and/or implantation recipe.

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1. Introduction

Photoconductive (PC) antennas gated with ultrashort optical pulses have been widely used as highly efficient emitters and detectors for terahertz (THz) pulsed radiation. The useful bandwidths of typical PC antennas were several THz [1,2]. This was extended up to 60 THz by Kono *et al.* [3,4] using sub-20 fs laser pulses, low-temperature-grown GaAs (LT-GaAs) PC antennas and a collinear geometry for THz and gating beams. Device-quality LT-GaAs, however, are still hard to come by. Alternatively, one can prepare photoconductive substrates by ion-implantation. Implanters are widely available and the process is reasonably reproducible. Recently, we demonstrated ultrabroad (>30THz) THz radiation detection using arsenic-ion-implanted GaAs (GaAs: As^+) photoconductive antennas [5]. However, the shallow arsenic ion-implanted layer (~100 nm), which was only 10% of the absorption depth (~ 1μm) at the excitation laser wavelength, resulted in lower signal to noise ratio (SNR) for THz detection. InP potentially can be an alternative to GaAs as the PC substrate material. Indeed, a PC antenna fabricated on semi-insulating InP (SI-InP) showed a higher responsivity and a SNR larger than 2 times than those of a LT-GaAs device in a regime of very weak probe laser power (~ 1 μW), although at higher probe power the LT-GaAs PC antenna out-performed the SI-InP one [6]. The degradation of SNR of SI-InP PC antenna at high probe laser power was attributed to PC saturation associated with the long carrier lifetime of InP (τ_{eff} ~70 ps). Low-temperature grown InP (LT-InP) was reported by Liang *et al* [7]. However, LT-InP was highly conductive, because of the n-type conductivity originating from the abundant presence of P_{In} antisites. Therefore, InP can be a good candidate as the PC substrate if it is sufficiently resistive and the carrier lifetime was shortened to that of LT-GaAs (~ 1 ps). This can be accomplished through ion-implantation. Lamprecht *et al.* [8] observed ultrashort carrier lifetimes in proton-bombarded InP (InP: H^+), which decreased monotonically with the dosage and was as short as 95 fs at the highest dosage (1×10^{16} cm^{-2}). Messner *et al.* [9] also showed that the photo-excited electron lifetime in InP: H^+ became less than a picosecond for proton dosages around $5x10^{15}$ cm^{-2}. The implantation depth of the protons in InP was estimated to be about 1.5 μm from the surface [8].

In this work, we investigate the performance of InP: H^+ PC antennas as the ultrabroadband THz detector. The bandwidth and SNR of the InP: H^+ PC antenna were compared to those of an LT-GaAs one and discussed in relation to the photoconductive gain and resistivity.

2. Experimental methods

Four InP: H^+ PC antennas were prepared by bombarding (100)-oriented SI-InP substrates with 180 keV proton with dosages of 1×10^{15}, 3×10^{15}, 1×10^{16} and 3×10^{16} ions/cm^2, respectively. The carrier lifetimes of all InP: H^+ and LT-GaAs samples used in this experiment were found

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to be shorter than 2 ps. A micro-stripline dipole antenna was fabricated on each InP:H$^+$ wafer by standard cleaning, metallization and lift-off procedures for InP. During the metallization processes, Ni-Ge-Au-Ge-Ni-Au metal layers were evaporated and annealed at around 400°C. The antenna consisted of 5-µm-wide coplanar striplines (6-mm long) separated by 20-µm and contacts, rectangular in shape, at the center of the coplanar striplines. The contact width and length (in vertical direction to the striplines) were 10 µm and 7.5 µm, respectively. The PC gap between the contacts was 5 µm. The experimental setup was as reported previously [4]. We employ a mode-locked Ti: sapphire laser (λ ≈ 800nm), generating a 15-fs (the spectral width was 95 nm or ~ 47 THz) pulse train at 75 MHz and an average output power of 400 mW. The pump beam was focused onto a 10-µm-thick (110) ZnTe crystal bonded on a 1-mm-thick fused silica plate by a gold-coated off-axis parabolic mirror with a focal length of 50 mm. The average pump power on the ZnTe emitter was 150 mW after mechanical chopping at 2 kHz. The gating laser power was 23 mW.

3. Results and discussions

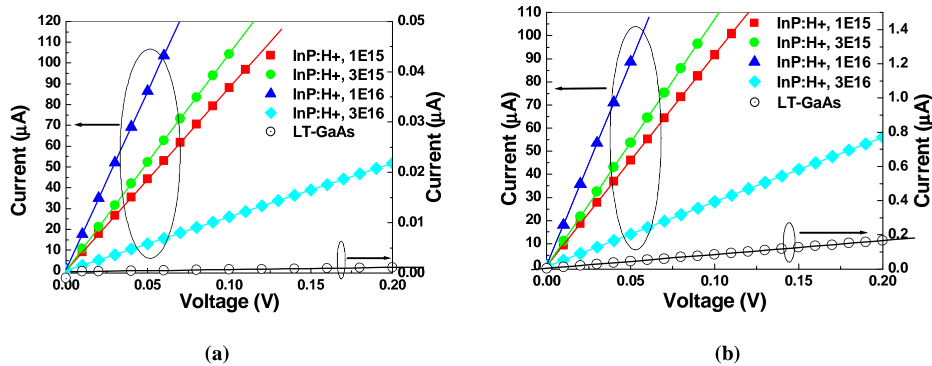

Fig. 1. Current-voltage (I-V) measurement (a) without and (b) with optical illumination for InP: H$^+$, doses of 10^{15} (square dot), 3×10^{15} (circle dot), 10^{16} (triangular dot), 3×10^{16} (diamond dot) ions/cm^2 and LT-GaAs (open circle) PC antennas with 5 µm gap in the weak bias case.

Figure 1 shows the current-voltage (I-V) characteristics for InP: H$^+$ and LT-GaAs PC gaps at nearly zero bias (< 0.2 V) without and with laser excitation. The linear I-V characteristics observed in the measurements for the four samples near zero bias field suggests that there should be no significant Schottky barrier effect, which can reduce the signal current due to the THz field biasing the PC antenna.[6] The resistance of the InP: H$^+$ PC gaps, which decreased as the ion dosage increased except for the case of 3×10^{16} ions/cm^2, and the LT-GaAs one are summarized in Table 1.

Table 1. Comparison of characteristics PC antenna detectors.

	LT-GaAs	**InP: H$^+$(1x10^{15})**	**InP: H$^+$(3x10^{15})**	**InP: H$^+$(1x10^{16})**	**InP: H$^+$(3x10^{16})**
Resistance (R) (Dark)	235MΩ	1.1 kΩ	0.97 kΩ	0.579 kΩ	3.8 kΩ
Resistance (R) (23mW illumination)	1.2 MΩ	1.07 kΩ	0.93 kΩ	0.568 kΩ	3.4 kΩ
Detected peak signal	0.24 nA	0.27 nA	0.15 nA	0.079 nA	0.082 nA
Detectable bandwidth	40THz	33THz	33THz	24THz	33THz
SNR	100	50	26	<12	40
Noise level	1	6.19	6.36	7.62	2.25

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The decreasing trend for InP: H^+ can be explained by the presence of the shallow defects, as our InP: H^+ samples were not annealed after the proton bombardment [10]. The resistance of InP: H^+ with the highest dosage (3×10^{16} ions/cm^2) was 4 times larger than other InP: H^+ samples. It was reported that the resistance of InP: H^+increased through annealing.[10] We thus tentatively attribute this increase in resistance to the self-annealing effect of implantation, by which the shallow defects were reduced at the highest dosage. It has also been demonstrated that annealing can reduce the defect density on arsenic-ion-implanted GaAs.[11] By the self-annealing mechanism, the shallow defect density might have also reduced in InP: H^+ prepared at the highest dosage. The stray current from InP: H^+ at dosages of 1×10^{15}, 3×10^{15}, 1×10^{16}, 3×10^{16} ions/cm^2 and LT-GaAs PC antennas were about 300 nA, 400 nA, 872 nA, 85 nA and 10 nA, respectively, at a gating power of 23 mW. The high conductance and the relatively low stray current of the InP: H^+ substrate with a dosage of 10^{15} ions/cm^2 implied a high responsivity and low noise.

The THz waveforms detected by each InP: H^+ and the LT-GaAs PC antenna are shown in Fig. 2. The detected THz peak signal currents are also listed in Table 1. The signal amplitudes in InP: H^+ PC antennas are all larger than our previous GaAs:As^+ device [5]. They are, however, in general lower than that of the LT-GaAs PC antenna except for the 1×10^{15} ions/cm^2 case. The decreasing trend and saturation in PC response with dosage has also been observed in PC switches fabricated on GaAs:As^+ [11].

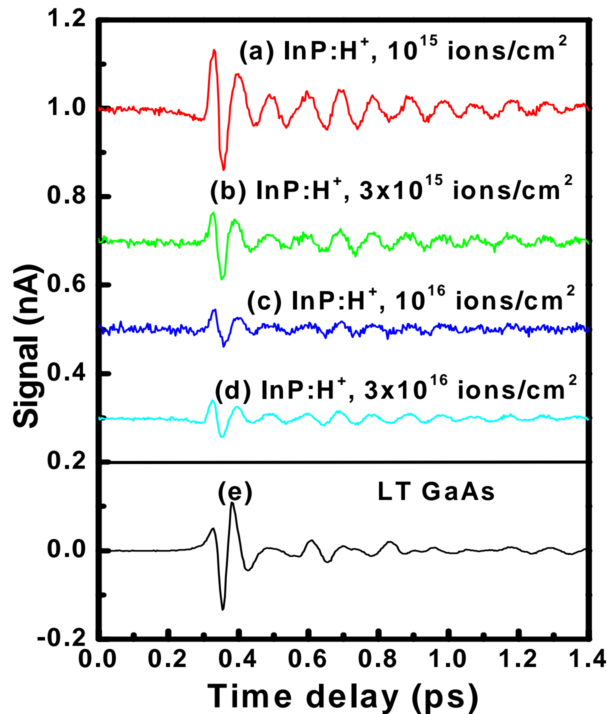

Fig. 2. Time-resolved ultrabroadband THz radiation waveforms detected by a PC antenna fabricated on InP: H^+ at doses of (a) 10^{15}, (b) 3×10^{15}, (c) 10^{16}, (d) 3×10^{16} ions/cm^2 and (e) LT-GaAs.

Figure 3 illustrates the Fourier transformed spectra of the PC-detected THz waveforms. The sharp spectral peaks around 9 THz and 10.4 THz observed for the LT-GaAs and InP: H^+ PC antenna, respectively, correspond to the LO-phonon frequencies of the substrates. The peaks are attributed to the optical phonon resonance effect: Near the LO-phonon frequency,

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the dielectric constant approaches unity and impedance mismatch between free space and the PC antenna (The static dielectric constants of InP and GaAs are 13 and 12.6, respectively) is alleviated. This results in higher signal strengths near these frequencies. The spectral dip observed around 5 THz is due to the transverse optical (TO) phonon (ω_{TO}=5.3 THz) in the ZnTe emitter. We also observe strong absorption at frequencies of TO phonons of InP (9.1 THz) and GaAs (8 THz). The origin of the peak around 13 THz is not clear. It may be associated with a water vapor absorption line at 12 THz [12]. The spectral dip observed at 15 THz is attributed to the absorption due to a oxygen impurity mode (The ν_2 bending mode of O_2 molecules around 15.5 THz) [13] in the Si plate used as the beam combiner for THz and optical probe beams. The dip at 18 THz is attributed to the two phonon (TO(L) + TA(L) or TO(X) + TA(X)) absorption in the Si beam combiner.

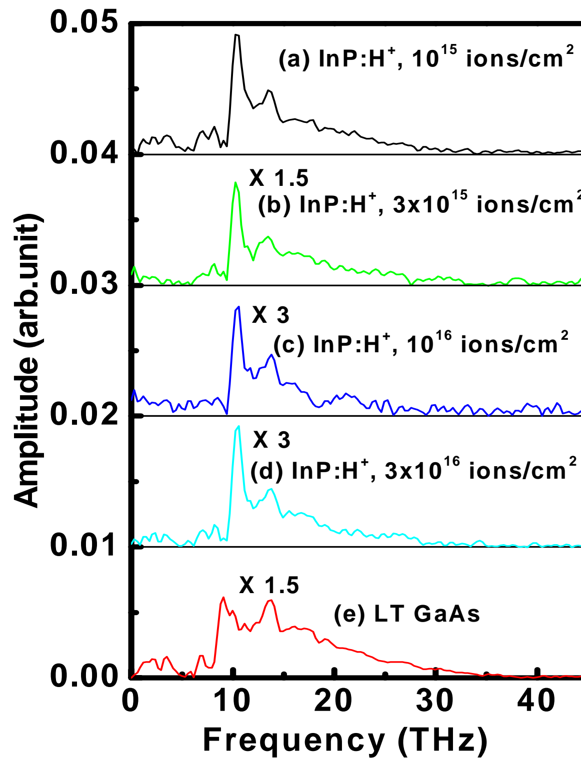

Fig. 3. Fourier transformed amplitude spectra of the PC-detected THz pulses shown in Fig. 2. Some spectra are enlarged for easier viewing.

The high frequency ends of the spectral distribution for each PC antenna are also summarized in Table 1. The bandwidth of the PC antennas is mainly limited by the laser pulse width [14]. The detectable frequency components at high frequency side are also limited by the noise level in the PC antennas. The noise level of InP: H^+ PC detectors relative to that of the LT-GaAs PC antenna increased as the resistivity decreased (see Table 1). The main contributions to the noise in a PC detector are from the Johnson noise (or thermal noise) and the laser shot noise [6]. The Johnson noise is inversely proportional to the square-root of the resistance, $1/\sqrt{R}$, while the laser shot noise is dependent on the laser power but not on the material properties of the PC substrate. We have plotted the noise against $1/\sqrt{R}$ in Fig. 4. The noise data fit well with a linear dependence, $J_{noise} = y_0 + m \times 1/\sqrt{R}$, with a slope of m =

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175 and an offset $y_0 = 0.3$ in the scale of Fig. 4. In the limit of high resistance the only contribution to the noise is the laser shot noise, which is given by the offset parameter y_0. The small y_0 indicates the noise in our PC antennas is dominated by the Johnson noise. The SNRs of the InP:H^+ PC atnenna, which are given by the ratios of spectral peak amplitude and the noise level, are summarized in Table 1. Although the low resistivity of InP: H^+ resulted in the high noise level, its high photoconductive gain partly compensates this drawback. An example is the SNR of the PC antenna using InP: $H^+(10^{15}$ ion/cm^2), which was about half of that with the LT-GaAs antenna, despite of the unfavorable resistivity ratio $\sqrt{R(InP:H^+)/R(LT-GaAs)}$ ~ 1/30.

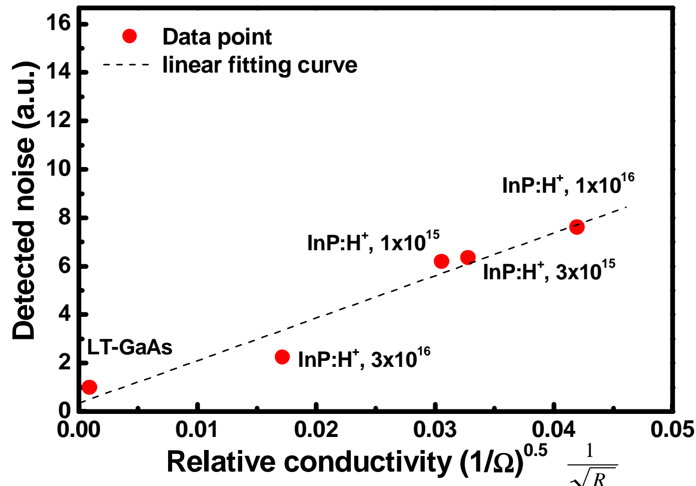

Fig. 4. Noise level of different InP: H^+ samples and relative to that of a LT-GaAs PC antenna are plotted as a function of conductance. Circle dot is the data point, dashed line is the fitting curve.

4. Conclusions

In summary, we have investigated the performance of InP: H^+ PC antennas as ultrabroadband THz wave detector. With THz radiation generated from a thin ZnTe emitter excited by 15-fs optical pulses, the detectable frequency distribution was confirmed to be about 30 THz. The peak THz signal of the InP:H^+ (10^{15} ions/cm^2) PC antenna is slightly higher than that of the LT-GaAs one, while the SNR of the former is about half as high as the latter. This can be improved by increasing the resistivity of InP:H^+ through optimizing the ion dosage level and/or the annealing condition. InP: H^+ could thus be a promising material as the photoconductive substrate for ultrabroadband PC antennas.

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