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Broadband and High Electric Field THz Pulse Emission from Photoconductive Emitters

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Abstract

We present Ge as a promising material for THz photoconductive emitters to push forward the limit of a gapless broadband spectrum from 6.5 THz to 13 THz. Maximum THz electric field reported so far from photoconductive technique is 36 kV/cm using a large-area interdigitated electrode based emitter. We also present here a better electrode design to enhance the THz electric field amplitude emitted from large-area interdigitated electrode emitters.

1. Introduction

The photoconductive technique provides one of the easiest ways for THz pulse generation and detection.[1, 2, 3] Compared to other techniques for broadband THz generation like optical rectification, air plasma or THz from liquids, it requires less pump pulse energy. Compared to quantum-cascade lasers and free-electron lasers the photoconductive technique is much more user friendly due to its compact size and room temperature operation. The quality of any THz emitter is characterized by signal-to-noise ratio, peak electric field in the THz pulse and its spectrum. The photoconductive technique has one more advantage over other THz generation techniques due to its ability of providing scattering-free easy electrical modulation for the lock-in detection to get a better signal-to-noise ratio. Due to these features the photoconductive technique is still the most popular technique for measurements requiring maximum signal-to-noise ratio despite the invention of new techniques for THz generation [4].

2. Photoconductive technique of THz generation

A dc electric field of the order of 10 kV/cm is applied in a photoconducting material with high carrier mobility, usually GaAs or InGaAs, using two electrodes. As shown in the schematic diagram in figure 1, the area between two electrodes is pumped by ultrashort laser pulses with sub-ps pulse duration to excite charge carriers in the photoconductor. The photo-generated charge carriers accelerate under the influence of already applied dc electric field and radiate a THz electromagnetic pulse. The THz pulse, radiated in the forward direction only, is collected and detected.

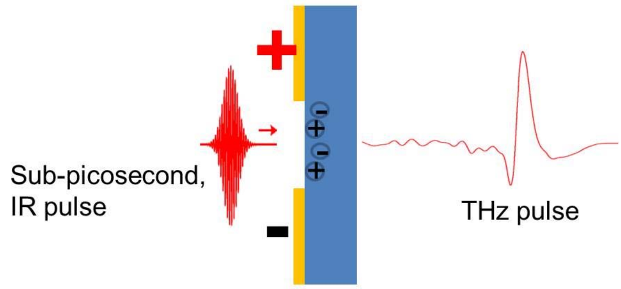

Figure 1. Schematic diagram illustrating THz emission from a photoconductive emitter.

3. Improving the bandwidth

Broadness of the spectral bandwidth of the THz pulses decides its versatility of application. The maximum bandwidth of a gapless spectrum from photoconductive emitters was 6.5 THz only. This limitation is due to the polar nature of the semiconductor crystal being used to fabricate the emitter. Most of the semiconductors used in THz technology, for example GaAs, InGaAs, ZnTe, GaP, GaSe etc., have polar nature; and hence their optical phonons are infrared (IR) active. Optical phonon frequencies of these materials are in the 5-10 THz spectral band. THz radiation around the phonon frequency of the emitter substrate gets strongly absorbed by exciting optical phonons, consequently limiting the spectral bandwidth of the THz pulse coming out of the emitter.

To overcome the bandwidth limitation due to IR active phonons, we use Ge, a semiconductor with nonpolar nature and high mobility, to fabricate photoconductive THz emitters. GaAs is also used to fabricate a reference emitter. Au (45 nm)/Ti (5nm) is deposited to form the electrodes. The gap between two electrodes is 10 µm and 10 V bias is applied on them. The emitters are pumped with 3 mW, 800 nm, ~ 65 fs, 250 kHz pulses from a Ti:Sa laser amplifier. A standard THz time domain spectroscopy (THz-TDS) setup is used to collect and detect the radiated THz pulses. 40 µm thin ZnTe <110> is used for electro-optic detection. THz pulses recorded in the time domain and corresponding Fourier transform spectra are shown in figures 2 and 3, respectively. The peak to peak electric fields of both pulses are roughly identical. The THz pulse in the time domain is shorter for the Ge emitter as compared to the GaAs emitter.

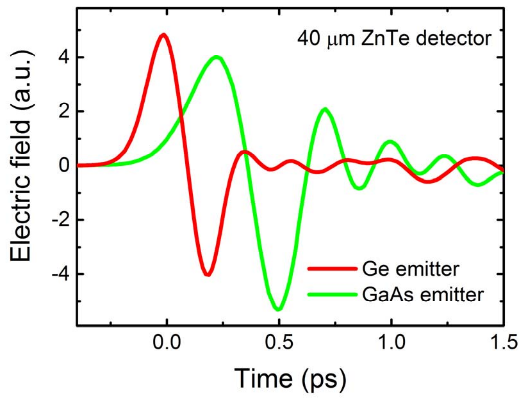

Figure 2. THz pulses emitted from GaAs and Ge emitters. The electric field profile of the pulses is recorded using 40 μm thick ZnTe for electro optic sampling in a THz-TDS set up (adopted from reference [6]).

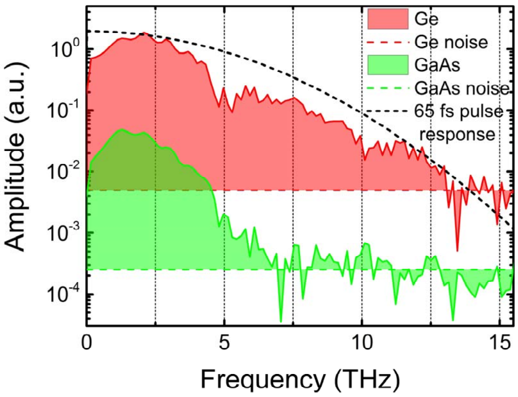

Figure 3. Fourier transform of the THz pulses shown in Figure 2. To get the true spectrum of the emitters, spectra after Fourier transform are corrected with the detector response function. Spectra are vertically shifted for visual clarity. The black dotted curve is frequency roll-off expected only due to the widths of pump and probe laser pulses (adopted from reference [6]).

Fourier transforms of time domain pulses are taken to study the spectral feature in the frequency domain. Spectra achieved after Fourier transformation also contain the detector response profile. The response of the ZnTe detector is frequency dependent. It is simulated as described in reference [5] and THz spectra are corrected by dividing by the simulated response function to get the true spectra of the THz emitters. The cut off frequency for GaAs is ~ 6 THz which is expected due to strong phonon absorptions between 7 and 10 THz in GaAs. For the Ge emitter we get a gapless continuous spectrum extending up to 13 THz, which is twice of the maximum bandwidth reported so far from any other photoconductive emitter. A small dip-like feature around 5 THz is due to a sharp dip in the ZnTe response which could not be corrected completely [6].

The frequency roll-off arising due to finite pump and probe pulse widths (~ 65 fs) is plotted with black dotted curve which also shows a roll off almost similar to the THz spectrum of Ge emitter. It means the actual spectrum from the Ge emitter could be broader than 13 THz if pumped with shorter IR pulses.

4. Improving the electric field

Higher electric field amplitude of the THz pulses improves data quality by increasing the signal-to-noise ratio and reducing the data acquisition time. It also widens the possible application of THz pulses reaching up to the nonlinear regime. Hence, it is always a concern for the researchers in the area to increase the THz field amplitude. The THz electric field from a photoconductive emitter depends on parameters like carrier mobility (μ), electic field (E_b) applied to the emitter and rate of change of free-carrier concentration *N(t)* (which depends on pump power):

$$E_{THz} \propto \frac{\partial N(t)}{\partial t} \mu E_b \qquad (1).$$

Different techniques have been used to increase the THz field. According to equation (1) higher THz field should be achieved by increasing the pump power to create a higher number of charge carriers within the short pump pulse duration. In practice photoconductive emitters show saturation effects with pump power at around 0.2 mJ/cm^2 optical fluence. To avoid this, one can increase the active area being pumped by increasing the electrode gap. But then the application of higher bias voltage is needed to get the same E_b. To overcome this issue large-area emitters with interdigitated electrodes have been used. To our knowledge the maximum THz electric field reported so far using such photoconductive emitters pumped with μJ energy pulses is 36 kV/cm [7]. The electrode structure of the interdigitated large-area emitter (iLAE) can be found in reference [8].

The iLAE consist of many individual strip line emitters. The overall efficiency of iLAE can be increased by increasing the efficiency of the individual strip line emitters, reducing the area occupied by each emitter and increasing the fraction of pump light actually falling in the active region. To optimize these parameters we have studied the performance of individual strip line emitters with different electrode parameters. Several strip line emitters with varying electrode widths from 2 μm to 50 μm are fabricated and their performance is compared. It is found that the THz amplitude increases with electrode width [9]. For further investigations emitters with asymmetric pairs of strip line electrodes are fabricated and tested with a 76 MHz Ti:Sa laser system running at 800 nm. Results are shown in Figure 3. It is observed that the THz field depends only on anode (+V bias) width and it is higher for wider anodes. The THz field is almost unaffected by changing the cathode (-V bias) width from 2 µm to 20 µm. By utilizing these asymmetric electrode structures in the iLAEs, the area occupied by each emitter can be reduced without affecting the performance of each individual emitter. In the reported iLAE with maximum THz field 38 kV/cm, only 25 % pump energy is being used to excite the charge carriers, the rest is being reflected by the metal electrodes. With the asymmetric electrode design reflection by the cathode area will be reduced and a higher fraction of pump energy can be used for THz generation.

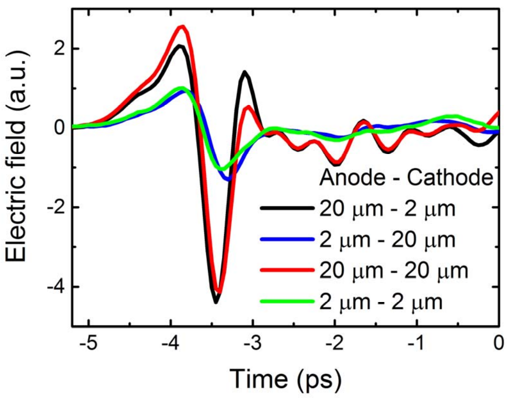

Figure 3. THz pulses emitted from strip line emitters with different anode and cathode widths. THz pulse profiles are recorded with ZnTe in a THz-TDS setup. Emitters are pumped with 25 mW pump power and 10 V bias is applied. The gap between two strip lines in earch emitter is 10 µm.

5. Conclusion

For practical applications of THz pulses, both high electric field amplitude and wider spectral band are useful. To obtain a wider and gapless THz spectrum, we demonstrate Ge as a promising material for photoconductive THz emitter. The gapless spectrum is enhanced by a factor of 2 as compared to any other photoconductive emitter, taking it from 6.5 THz to 13 THz. To enhance the THz electric field amplitude from photoconductive emitters, we demonstrate strip line emitters with asymmetric electrode width, which could improve the performance of iLAE which has reported maximum electric field amplitude so far from any photoconductive THz emitter.

6. Acknowledgements

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7. References

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