Reduction of phonon resonant terahertz wave absorption in photoconductive switches using epitaxial layer transfer

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A broadband terahertz time-domain spectroscopy (TDS) system for frequencies of up to 15 THz, including the phonon resonance frequency range, has been developed using a transferred thin-film photoconductive switch (PCS) detector. The thin-film PCSs, based on low-temperature-grown GaAs, were fabricated using epitaxial layer transfer onto high-resistivity Si substrates. We observed a reduction of phonon resonant absorption, including between 7 and 10 THz, in a forward radiation configuration. Numerically calculated absorption spectra show good agreement with our experimental results. This technique will provide compact, broadband TDS systems. © *2009 American Institute of Physics*. [DOI: 10.1063/1.3103278]

The generation and detection of ultrabroadband terahertz pulses have been studied using various approaches.[1–10] Generation by optical rectification and detection by electro-optic sampling using nonlinear crystals are typical methods.[1–3] Photoconductive switches (PCSs) are employed as emitters[4,5] and detectors.[6,7] Using laser-induced plasma is a newly developed method covering the frequency range between 0.2 and 12 THz.[8] However, a high-power (typically above 100 mW) excitation laser is necessary to generate terahertz pulses by optical rectification. Furthermore, a regenerative amplifier of femtosecond laser pulses is necessary to create plasma in air.

Although PCSs need only low-laser power, GaAs constituents of PCSs have a phonon resonance around 8 THz that generates a broad absorption band between 7 and 10 THz. PCSs emit forward and backward terahertz radiations, propagating in the same and opposite directions to the excitation laser propagation, respectively. Although using backward radiation minimizes phonon resonant absorption,[4] backward radiation is weaker than forward radiation. Furthermore, a complex optical configuration is needed.

To solve this problem, we have developed epitaxial layer transferred (ELT)-PCSs.[9] Low-temperature-grown (LT)-GaAs epitaxial layers are transferred onto high-resistivity Si substrates to enable PCSs to avoid terahertz wave absorption in the GaAs substrates. ELT-PCS detectors showed higher sensitivity than conventional PCSs at high frequencies, but a direct investigation in the phonon resonance frequency range was not undertaken.

In this paper, we describe broadband terahertz time-domain spectroscopy (TDS) for frequencies of up to 15 THz using an ELT-PCS detector. We detected broadband terahertz pulses, including frequencies of 7–10 THz, with a Si hemispherical lens in a forward radiation configuration.

ELT-PCSs (see Fig. 1) were fabricated as follows. AlAs and LT-GaAs layers (2 μm thick) were grown on a GaAs substrate by molecular beam epitaxy, and a dipole antenna was formed on the surface of the LT-GaAs layer. Then, it was pasted using wax on a glass substrate with the antenna side down, and the GaAs substrate was removed by selective wet etching. The exposed LT-GaAs thin film was bonded to a Si substrate using epoxy-based adhesive (thickness of $\sim$60–70 μm). Finally, the glass substrate and wax were removed by solvent.

Figure 2 shows the experimental setup of the terahertz-TDS measurement system. The broadband terahertz emitter was the organic crystal 4-N,N-dimethylamino-4′N'-methyl-stilbazolium tosylate (DAST) with 1.55 μm fiber laser-based ultrashort-pulse irradiation.[10] A split beam was input to the periodically poled lithium niobate (0.6 mm thick, 100 °C) to generate 0.78 μm pulses to operate a PCS detector. The pulse width (averaged power) of the fundamental and the frequency-doubled pulse was 17 fs (100 mW) and 30 fs (10 mW), respectively. A metal pole 5 mm in diameter was inserted between the two parabolic mirrors to block the optical pulses through the DAST crystal. Water vapor was purged using dried nitrogen.

The acquired terahertz wave forms and the corresponding Fourier transform spectra are shown in Fig. 3. The broadband terahertz spectra for frequencies of up to 15 THz were obtained. The dip around 4.5 THz is thought to be an artifact because its existence depends on the alignment of the parabolic mirrors and the metal pole.

Phonon resonant absorption between 7 and 10 THz was clearly observed in the spectrum obtained by a conventional PCS with a 2-μm-thick LT-GaAs layer on a 500-μm-thick GaAs substrate (see Fig. 3). In contrast, the ELT-PCS shows

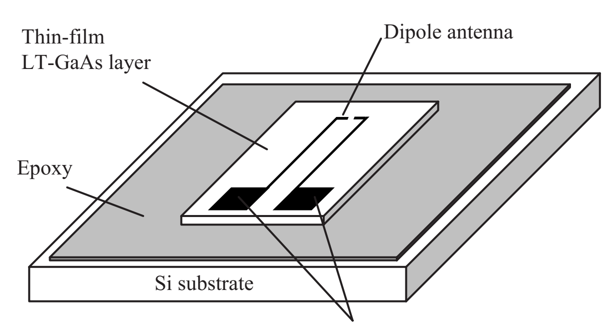

FIG. 1. Schematic illustration of an ELT-PCS. A thin-film LT-GaAs layer with an antenna is bonded onto a Si substrate with epoxy adhesive.

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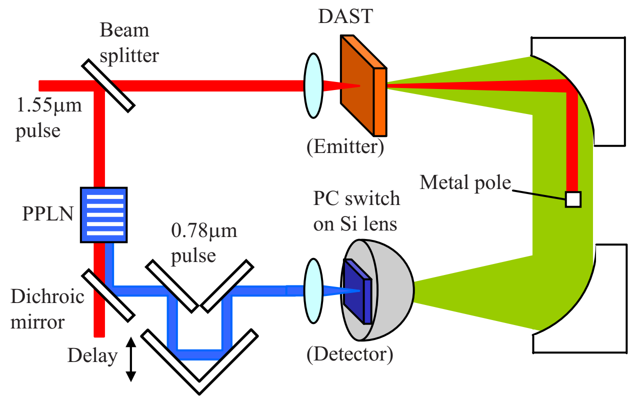

FIG. 2. (Color online) Experimental setup of broadband terahertz-TDS. Terahertz pulses were emitted from a DAST crystal using a 1.55 μm wavelength ultrashort-pulse fiber-based laser. A detector PCS was operated by frequency-doubled ultrashort-pulse laser.

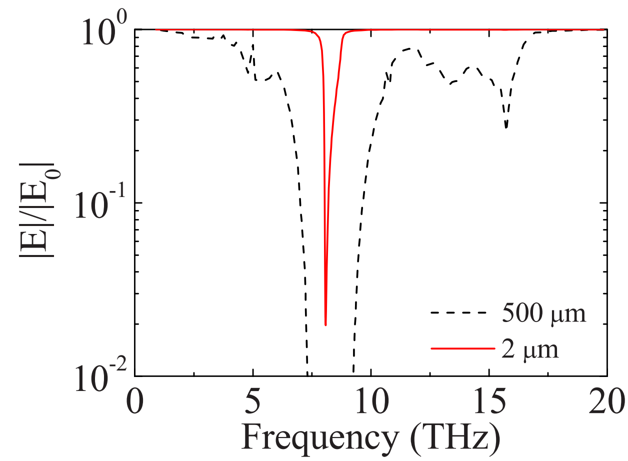

FIG. 4. (Color online) Calculated absorption spectra of GaAs due to phonon resonance using handbook data. (Ref. 11) Solid and dotted lines show calculations for GaAs thicknesses of 2 and 500 μm, respectively. The absorption line and band widths at 10 dB above the bottom of the absorption line are 0.29 and 3.15 THz, respectively. The corresponding widths of experimental data in Fig. 3 are 0.52 and 3.37 THz, respectively.

only a narrow absorption line around 8 THz. The terahertz time-domain wave form of the conventional PCS was of the multipulse-type, while that of the ELT-PCS exhibited a monocycle with a pulse duration of approximately 170 fs (full width at half maximum).

The magnitude of the electric field of the detected terahertz waves in the frequency domain $E_d(\omega)$ is given by

$$E_d(\omega) = E_i(\omega)W(\omega)\exp\left[-\frac{\alpha(\omega)d}{2}\right], \tag{1}$$

where $E_i(\omega)$ is the magnitude of the electric field of the incident terahertz waves, $W(\omega)$ is the antenna characteristic, α is the absorption coefficient, and d is the thickness of the GaAs layer. Note that α is defined as the intensity absorption in a medium and must be divided by two for the electric field. To verify the effect of the substrate conversion, the normalized GaAs absorption spectra $\exp[-\alpha d/2]$ are calculated using complex refractive index data,[11] as shown in Fig. 4. The thickness of the GaAs substrate and the LT-GaAs layer are assumed to be 500 and 2 μm, respectively. In the 7–10 THz range, the calculations show good agreement with the experimental absorption spectra shown in Fig. 3. The absorption frequencies of the ELT-PCS in the experiment and numerical calculation are 8.10 and 8.09 THz, respectively,

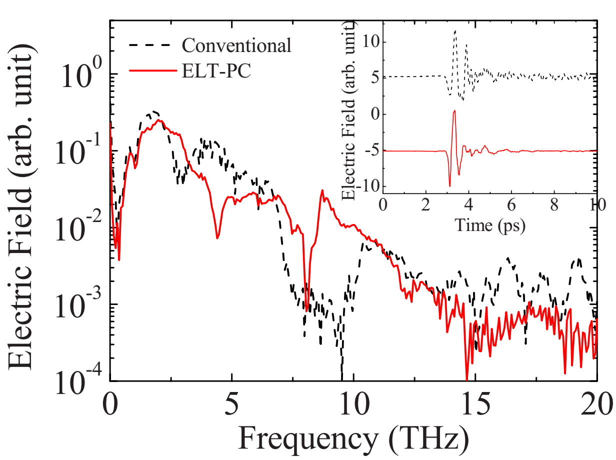

FIG. 3. (Color online) Terahertz time-domain wave forms (inset) and corresponding Fourier transform spectra. The absorption band of 7–10 THz of the conventional PCS (dotted line) was reduced by replacing it with an ELT-PCS (solid line), except for the sharp absorption at 8 THz.

with absorbance of approximately 1.5 dB around 8 THz in both cases. The remaining absorption line is attributed to the existence of the LT-GaAs layer. The sharp dip in the ELT-PCS is located almost exactly at the transverse optical phonon frequency (8.05 THz) of GaAs.[12] A thinner LT-GaAs layer can reduce the absorption. According to Eq. (1), the transmittance will increase from 2 % to 14 % when the thickness is decreased from 2 to 1 μm.

The LT-GaAs layer, the midlayer (epoxy), and the Si substrate form an etalon resonator with the free spectral range (FSR) of the interference being

$$\mathrm{FSR} = \frac{c}{2nd' \times 10^{-6}} \cong \frac{100}{d'} \quad (\mathrm{THz}), \tag{2}$$

where c is the speed of light ($\sim 3.0 \times 10^8$ m/s), n is the refractive index of the midlayer medium in the terahertz frequency range (~ 1.5), and d' is the midlayer thickness in microns. In this experiment, the FSR of the ELT-PCS is 1.54 THz, assuming $d' \sim 65$ μm. However, the spectrum of the ELT-PCS showed no fringe (see Fig. 3) as the influence of the interference on the spectrum is smaller than that of the alignment artifact and the LT-GaAs phonon resonant absorption. Note that according to Eq. (2), the FSR of an ELT-PCS with a midlayer thinner than 10 μm is larger than 10 THz.

In summary, we have developed an ELT-PCS with reduced phonon resonant absorption. In a forward radiation configuration, the ELT-PCS detected broadband terahertz pulses, including frequencies between 7 and 10 THz, except for a sharp absorption line around 8 THz. The experimental absorption spectra showed good agreement with numerical calculations. A thinner LT-GaAs substrate will reduce the remaining absorption around 8 THz. The desired thickness of the midlayer is less than 10 μm. Chip bonding with epoxy was used in this experiment, but solid-phase wafer bonding will produce thin midlayer ELT-PCSs efficiently. This technique can be applied to InGaAs and other materials. ELT-PCSs will also work as emitters. It is expected that ELT-PCSs can be used to produce compact, low-laser power, and broadband terahertz-TDS systems without a phonon resonant absorption band. This technique will expand the capabilities of terahertz-TDS and related techniques.

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