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2002 Jpn. J. Appl. Phys. 41 L1158

(http://iopscience.iop.org/1347-4065/41/10B/L1158)

Jpn. J. Appl. Phys. Vol. 41 (2002) pp. L 1158–L 1160
Part 2, No. 10B, 15 October 2002

Characteristics of Photogenerated Bipolar Terahertz Radiation in Biased Photoconductive Switches

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(Received May 29, 2002; accepted for publication August 19, 2002)

The characteristics of the optically induced bipolar terahertz (THz) radiation from biased semi-insulating GaAs photoconductive switches were investigated using a free-space electrooptic sampling technique. The emitted radiation shows a nearly symmetrical waveform with a broad-band frequency spectrum spanning over 0.1–3 THz, which displays essentially no dependence on the optical excitation fluence or strength of biased field. However, it does slightly depend on the emitter gap spacing. The dynamics of the emitted THz transient is in agreement with the optically induced ultrafast charge transport process driven by the biased field. [DOI: 10.1143/JJAP.41.L1158]

KEYWORDS: THz radiation, bipolar, photoconductive switches, free-space electrooptic sampling, ultrafast laser pulse illumination

Broad-band coherent terahertz (THz) radiation emitted from biased photoconductors after excitation by an ultrafast laser pulse[1–3] has been used as a spectroscopic tool for characterizing carrier transport in semiconductors,[4,5] examining gap and subgap features of superconductors,[6,7] and for the emerging applications of coherent THz imaging.[8] The emitted THz waveforms and frequency spectrum of the biased photoconductive switches have been studied by several groups.[5,9] Under some particular conditions, bipolar THz waveforms were obtained both in large- and small-aperture photoconductive switches. Usually, both large- and small-aperture photoconductive switches are defined to have an optically illuminated area of dimensions comparable to the center wavelength of the emitted radiation. The mechanism of the photoinduced THz radiation, however, is still a matter of debate. For instance, the reason why the emitted waveforms can exhibit unipolar and bipolar characteristics has provoked some exotic interpretations.[9] In order to clarify some of the controversial issues, it is of interest to carry out systematic comparisons between the emissions generated with different operating parameters.

In this paper, THz radiations obtained from biased photoconductive switches with various emitter gap spacings, applied bias fields and optical excitation fluences are reported. Our results showed that with the gap spacing ranging from 10–500 μm, the emitted radiations are all bipolar in nature. Furthermore, the waveform and the frequency spectrum distribution do not depend on the optical excitation fluence or strength of the biased field. This suggests that the THz radiation obtained in the current setup originates from essentially the same mechanism as that associated with the ultrafast charge transport process during pulsed laser illumination. Namely, by biasing a constant voltage across the gap spacing of the emitter, carriers photoinjected into the gap by ultrafast laser pulse will be accelerated, leading to the emission of a transient and broad-band frequency THz radiation.

The experimental setup for the generation and detection of THz radiation using a free-space electrooptic sampling[8,10] system is illustrated schematically in Fig. 1. A CW argon-laser-pumped, compact mode-locked Ti:sapphire laser (femtosource C20) provides 20 fs optical pulses at 800 nm (1.55 eV) with a 75 MHz repetition rate. The pump beam aligned at normal incidence is modulated by a mechanical chopper opterated at 1.3 kHz. The electric field of a THz pulse is sampled by scanning the delay between the pump and probe beam. An undoped semi-insulating GaAs (SI-GaAs) photoconductive emitter, triggered by femtosecond laser pulses, radiates the THz beams. The emitted radiation is collimated and focused by a pair of off-axis paraboloidal mirrors onto the ZnTe sensor crystal. The Au/Ge metal patterns of the planar emitters are obtained by standard lift-off procedures. A 5-μm-thick pellicle beamsplitter, which is transparent to the THz beam, is used to reflect 50% of the synchronized optical probe beam collinearly along the THz beam. The polarized THz and probe beams are aligned to a 1-mm-thick $\langle 110 \rangle$-oriented ZnTe sensor crystal. We used a quarter-wave plate to impart a $\lambda/4$ optical bias to the probe beam, which allows the system to be operated in the linear range. A Wollaston polarizer is used to convert the THz-field-induced phase retardation of the probe beam into an intensity modulation between the two mutually orthogonal linearly polarized beams. The optical intensity modulation is detected using balanced photodiodes in a digital lock-in amplifier (SR830).

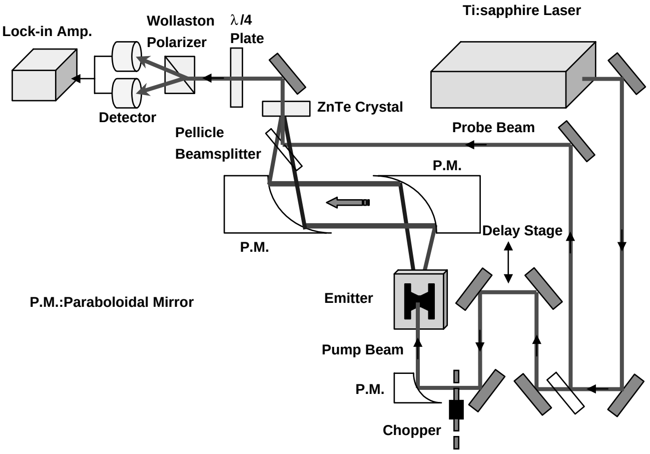

Fig. 1. Schematics of the experimental setup of free-space electrooptic sampling system.

Figure 2 shows the typical photogenerated THz signals as a function of the scanning delay time obtained from the semi-insulating GaAs photoconductive switches with a biased field of 2 kV/cm. The average pumping powers (fluences) are (a) 130 mW (0.8 μJ/cm^2) and (b) 1 mW (60 nJ/cm^2). The gap

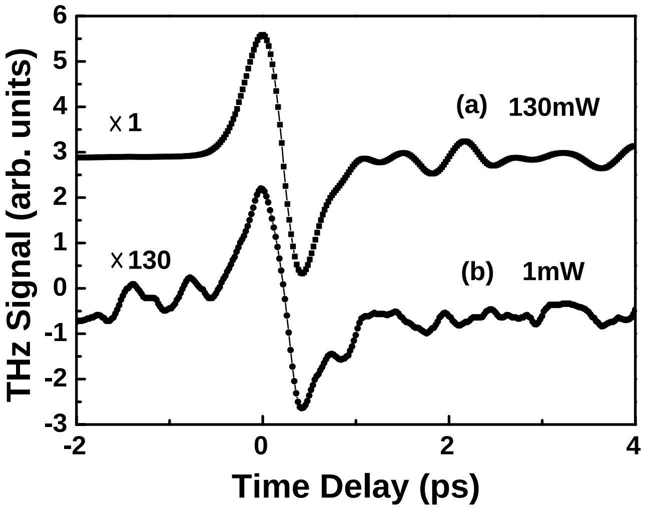

Fig. 2. Transient THz waveforms for 500 μm gap spacing photoconductive switches. The average pumping power is (a) 130 mW and (b) 1 mW.

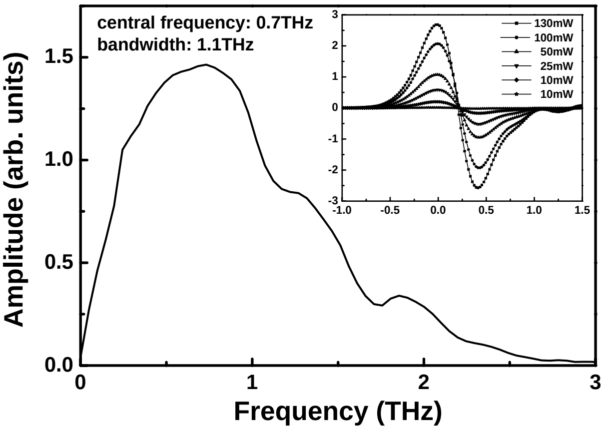

Fig. 3. Corresponding frequency spectrum by Fourier transform of the THz waveforms. The inset shows a series of emitted THz waveforms obtained at various average pumping powers for 500 μm gap spacing photoconductive switches.

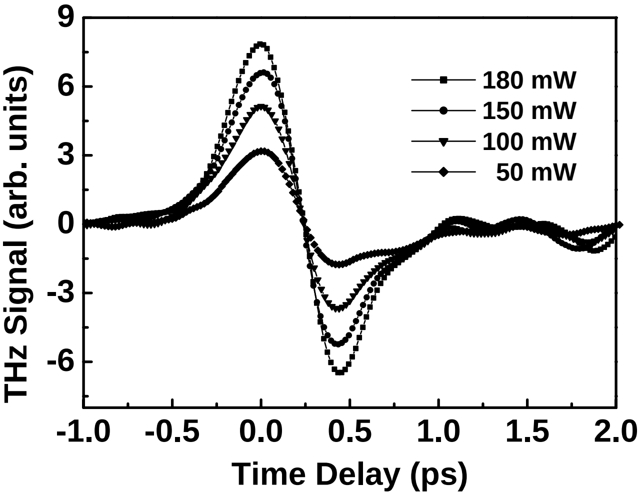

Fig. 4. A series of emitted transient THz waveforms for 10-μm-wide photoconductive switch.

spacing of this emitter is 500 μm. Nearly symmetrical THz waveforms are observed. The signal-to-noise ratio (SNR) is about 10^3 (10^6 in power) for the 130 mW case. In contrast, for the 1 mW case, strong noise is observed before delay time $t = 0$. There are some secondary peaks not shown here that appeared after about 15 ps delay of the main THz signals, which are believed to arise from substrate multiple reflections.

Usually, when a femtosecond laser pulse illuminates the semiconductors with a photon energy greater than the band gap (for SI-GaAs, band-gap $E_g = 1.42$ eV), photons are absorbed, thus creating electron-hole pairs. The external biased field drives the photogenerated carriers to form a transient photocurrent across the field region. Namely, a radiated THz electric field is obtained by the time derivative of the net current. It acts as the source term in Maxwell's equations. In Fig. 2, an integrated THz pulse is sampled about 2 ps. The rise time (the full width of half-maximum (FWHM) is 310 fs) and fall time of the photocurrent are 0.9 ps and 1.2 ps, respectively. The carrier transient time across the biased field width is obviously much shorter than the carrier lifetime ($\sim$ 100–300 ps). This cannot be explained by attributing the effects to carrier lifetime as was proposed by Budiarto *et al.*[11)]

Figure 3 shows the representative power spectrum derived by Fourier transform of the THz waveforms. The radiation frequency spectrum extends from 0.1 THz to 3 THz. The central frequency is 0.7 THz and the region of maximum intensity distribution of the spectral pattern lies in the range of 0.4–0.9 THz. The bandwidth of half-maximum (BWHM) of the frequency spectrum is around 1.1 THz. The inset of Fig. 3 shows plots of a series of emitted bipolar THz radiations as a function of average pumping power for the 0.5-mm-wide photoconductive switch. It is evident that the symmetrical THz waveforms remains intact over the whole range of optical excitation fluences studied. Moreover, the peak strength of the emitted THz field increases linearly with optical excitation fluence. The absence of amplitude saturation, as observed by Darrow *et al.*,[1)] may be due to the smaller excitation fluences used here.

From the above results, it is evident that, in large-aperture photoconductive switches, the bipolar nature of the THz radiation waveforms is independent of pumping power. It is thus interesting to see whether the waveforms and frequency spectra would change with the emitter gap spacing. Figure 4 shows a series of emitted bipolar THz radiations as a function of average pumping power for the 10-μm-wide photoconductive switch. As can be seen, the slightly unsymmetrical THz waveforms remain intact over the whole range of optical excitation fluences studied. Nearly the same ratio of the THz pulse for the positive lobe to that for the negative lobe is obtained under different optical excitation fluences for a 10 μm emitter gap spacing. For 100 μm gap spacing photoconductive switches (not shown here), similar behaviors are also observed. Since the size of the laser spot is about 500 μm and 30 μm for 500 μm and 10 μm gap spacing switches, respectively, the current results display no signature of unipolar to bipolar waveforms transitions.[5)]

Since the waveforms are essentially the same for all cases, it is suggested that the broad-band frequency spectrum of the emitted radiation is not dependent on either the excitation fluences or the emitter gap spacing. In addition, experiments have shown that the waveforms and frequency spectrum of the emitted radiation display no dependence on the strength of the biased field. In our measurement configuration, the optical pumping (800 nm) is incident normal to the emitter substrate so that the radiation output is independent of surface depletion and difference frequency mixing due to the surface $\chi^{(2)}$ of photoconductors.12) The robust characteristics of the emitted radiation indicate that the same underlying physical mechanism prevails in all cases.

In fact, similar results have been reported by Lu *et al.*8) for a 2.5-mm-wide emitter using the free-space electrooptic sampling technique. These, however, are in sharp contrast with some of the results reported in literature. It has been proposed that bipolar waveforms of THz radiation, which can only appear in large-aperture photoconductors with high optical excitation fluences, are a consequence of space-charge screening of the bias field.9) On the other hand, Pederson *et al.*5) studied the effects of carrier density on the emitted waveform for a 50-μm-wide emitter and concluded that the emitted radiation changes from unipolar to bipolar with increasing photoexcited carrier density. In our case, a bipolar nature of THz radiation is obtained, and the fall time of the transient photocurrent seems to be independent of the different operating parameters. In another word, the carrier transient time across the biased field width, in either the 500-μm- or 10-μm-wide photoconductive switch, is very fast and much shorter than the carrier lifetime. Since the bipolar nature of the THz radiation obtained in the current setup persists in virtually every case studied, the current results can be interpreted consistently in terms of the mechanism associated with the ultrafast charge transport process during pulse laser illumination. The apparent discrepancies mentioned above may arise merely from detection and sampling techniques. It is noted that the alignment for the generation and detection of THz radiation must be handled very carefully for the 10 μm gap spacing emitter in the experimental process. The laser spot of focused optical normal incidence may partly pass through the substrate and be detected by the system at higher fluences. Such a situation may have blurred the actual signals from the photogenerated radiation.

In conclusion, the characteristics of optically induced bipolar THz radiation in biased photoconductive switches were investigated systematically by a free-space electrooptic sampling technique. It was observed that the bipolar nature and the emitted frequency spectrum distribution remained unchanged on varying the optical excitation fluence, strength of the biased field and the emitter gap spacing. These results are in agreement with the dynamics of the optically induced ultrafast charge transport driven by the biased field.

This work was supported by the National Science Council of Taiwan, R.O.C. under grants NSC90-2112-M-009-030 and -036.

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