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Improved sensitivity of terahertz detection by GaAs photoconductive antennas excited at 1560 nm

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The terahertz detection by photoconductive antennas (PCAs) based on low-temperature grown (LTG) GaAs with 1.5 μm pulse excitation was revisited. We found that the detection efficiency can be improved by a factor of 10 (20 dB) by reducing the excitation spot size and the gap length of the PCA, maintaining the low noise feature of the PCA on LTG GaAs. As a result, the signal-to-noise ratio higher than 50 dB was obtained at a reasonable incident power of 9.5 mW, suggesting that the scheme is promising for the detection of terahertz waves in practical time domain systems. © *2010 American Institute of Physics*. [doi:10.1063/1.3519480]

The use of mode-locked fiber lasers emanating femtosecond pulses in 1.5 μm band for the generation and detection of terahertz waves has led to the compact, stable, and portable terahertz time domain spectroscopy (TDS) systems. In most of the systems, however, the laser output is upconverted to 800 nm range because of the lack of good emitter and/or the detector that can be directly activated by the 1.5 μm pulses. To get the most out of the merit of using fiber lasers, the development of the emitters and detectors directly excitable at 1.5 μm is strongly desired. For the emitter, several candidates have been investigated and proven to work well: InGaAs-based photoconductive antennas (PCAs) including the ones prepared with ion-implantation,[1–3] low-temperature-growth with Be doping,[4,5] incorporation of ErAs clusters,[6] and Fe-doping,[7] as well as the optical rectification in nonlinear crystals[8,9] and the semiconductor surface such as InAs and InSb.[10] On the contrary, there has been a smaller number of reports on the detector. Except for the electro-optical sampling in GaAs,[8] the detectors investigated have been the PCAs on the InGaAs films similar to the ones used in the emitter[5,11,12] because InGaAs can be excited directly at 1.5 μm. However, in spite of the efforts on the material preparation, the resistivity in the InGaAs films is still around 1 kΩ cm,[12] which is significantly lower than that in the low-temperature-grown (LTG) GaAs, causing the higher noise level of the detector.

On the other hand, it has been reported that PCAs on LTG GaAs can also detect the terahertz waves even with 1.5 μm excitation through a nonlinear photocarrier generation.[13] However, the method has not been used in practical terahertz TDS systems because the signal amplitude is about an order of magnitude smaller than that with 780 nm excitation.[13] The PCA used in their experiment is a dipole type having a gap length of 5 μm, which is a standard design widely used. In this article, we report that the response can be enhanced by focusing the probe beam tightly on the PCA of reduced gap length. It will be shown that by reducing the spot diameter and the dipole gap from 5.4 and 5 μm to 2.7 and 1.5 μm, respectively, the signal amplitude is enhanced by a factor of 10, almost recovering the reported smaller efficiency, at a reasonable excitation power (pulse energy) of 9.5 mW (0.2 nJ).

The dipole type PCAs were fabricated on LTG-GaAs films of 2 μm thickness grown on a GaAs substrate using a conventional photolithography and a lift-off technique. The dipole is embedded in a coplanar stripline, as usual, through which the terahertz field-induced photocurrent is read out, as shown in Fig. 1(a). We tested the PCAs having the gap length L_G of 1.5, 3.0, 5.0, and 10 μm. The width W_G of the dipole gap was chosen to be the same as L_G, except for the case of L_G=1.5 μm for which W_G=2 μm.

The terahertz detection by the PCAs was performed using a standard time domain setup equipped with a mode-locked fiber laser (IMURA B-200) of which the center wave-

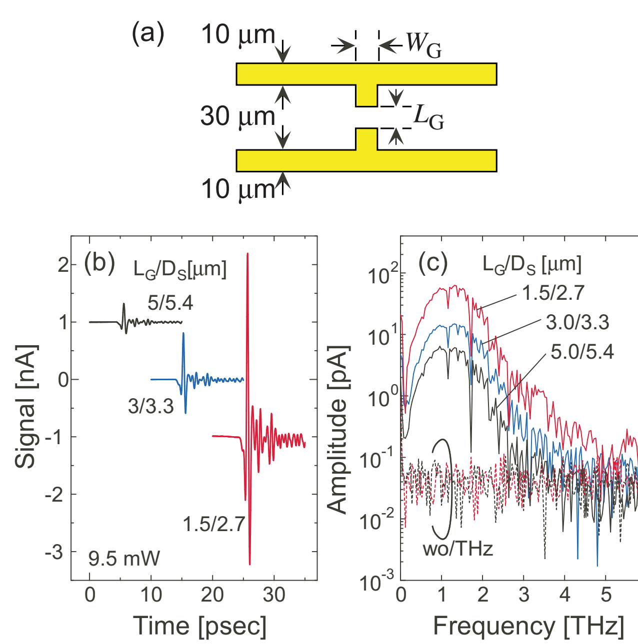

FIG. 1. (Color online) (a) Schematic illustration of the photoconductive antenna. (b) Time domain traces of the observed terahertz signals. The traces were shifted vertically and horizontally for clarity. (c) Amplitude spectra of the time domain traces.

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length, the pulse width, and the repetition rate are 1560 nm, about 60 fs at the laser output, and 50 MHz, respectively. As the emitter of the terahertz waves, we used a 50-μm-long dipole PCA on LTG GaAs driven at 780 nm by the second harmonic of the laser output generated in a periodically poled $LiNbO_3$ crystal. The width and the length of the PCA gap are 5 and 10 μm, respectively. The 780 nm light and the other harmonics in the probe beam line were suppressed by orders of magnitude by two long-pass filters inserted in series. All the results of the terahertz measurement shown below were obtained with a bias of 30 V and an excitation of 5 mW for the emitter and 10 ms time constant of the lock-in amplifier, without purging the air in the terahertz path.

To obtain various spot sizes of the probe beam on the detector PCA, we used several microscope objective lenses, for which the minimum spot size was measured in the time domain setup by the knife-edge method. The spot size D_S denoted in this paper is the minimum $1/e$ diameter at the focal point. In the terahertz measurement, the focusing of the probe beam was adjusted so as to get the largest signal amplitude. In this paper, we denote the combination of the gap length and the diameter of the excitation spot for the receiver antenna by L_G/D_S, both of which are given in units of micrometer.

Shown in Fig. 1(b) are the time domain traces of the terahertz waves for several combinations of D_S and L_G with a detector excitation of 9.5 mW. It is clear that the use of the small D_S combined with the short L_G leads to the significant enhancement in the signal amplitude. In particular, the combination of L_G/D_S=1.5/2.7 gives a peak-to-peak amplitude reaching 5 nA, which is in the same order as that obtainable with the 50-μm-long dipole PCA excited at 780 nm.[13] The amplitude spectra of the traces are shown in Fig. 1(c). The peak amplitude around 1 THz obtained with the combination of L_G/D_S=1.5/2.7 is enhanced by a factor of 10 in comparison with the L_G/D_S=5.0/5.4 case, without an apparent degradation of the spectral width.

The dotted curves in Fig. 1(c) are the spectra obtained without the terahertz waves, representing the noise level of the detection system. As shown later, this level does not depend on the excitation power, the gap length, and the spot size in the ranges investigated here. In the case of L_G/D_S =5.0/5.4, the terahertz spectrum falls down to this level around 3 THz. In the L_G/D_S=1.5/2.7 case, on the other hand, the spectral tail in the high frequency region is pushed up, indicating the presence of excess noise. As a result, the peak-to-noise ratio does not increase as the signal does with reducing the spot size and the gap length. Nevertheless, the combination of L_G/D_S=1.5/2.7 gives the ratio higher than 50 dB, which is a good value for the 10 ms lock-in time constant. Although the origin of the excess noise is not clear at present, it can come from the fluctuation of the spot position of the probe beam on the PCA, which is significant in such a tightly focused excitation. If it is the case, the excess noise can be reduced by making the setup compact and fixing tightly the optics as in the commercial systems.

The peak-to-peak amplitude in the time domain trace was plotted in Fig. 2 as a function of D_S for various combinations of D_S and L_G including those not shown in Fig. 1. It is clearly seen that the reduction of the spot size is effective for enhancing the signal. In addition, we can notice that L_G should be appropriately chosen for a given D_S, or inversely D_S for a given L_G. Specifically, for L_G=1.5 μm, the choice

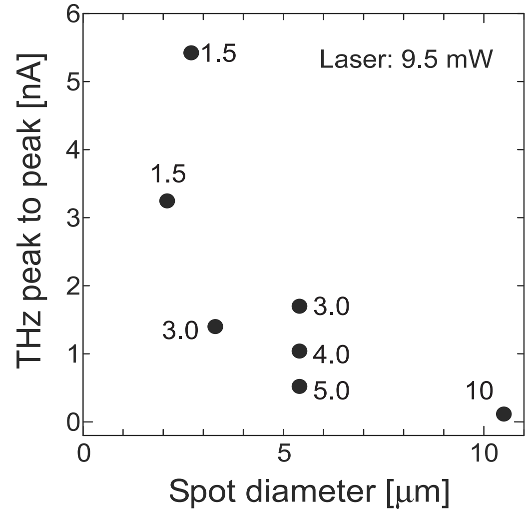

FIG. 2. Peak-to-peak amplitude in the time domain traces as functions of the spot size of the probe pulses. The numerical values are the gap length of the antenna.

of D_S=2.7 μm is obviously better than D_S=2.1 μm.

The excitation power dependence of the peak-to-peak terahertz amplitude is shown in Fig. 3(a) and that of the conductance of the PCA at a 0.1 V bias in Fig. 3(b). Both the signal amplitude and the photoconductance increase as P^n with $n \sim 1.35$ for the incident power P, indicating that the origin of the terahertz detection in the LTG GaAs is the nonlinear photoresponse. The value of n smaller than 2 suggests that the photoexcitation process is not a pure two-photon absorption but the one involving the real excitation at the midgap states formed by the excess As atoms.[13] Indeed, we confirmed that a meaningful signal cannot be obtained with the PCA made on semi-insulating (undoped) GaAs substrate. In the case of L_G/D_S=1.5/2.7, a signature of saturation is seen in the large signal regime. However, the saturation behavior is not clear in the L_G/D_S=1.5/2.1 case, where the excitation density is even higher. Hence, further experiments are necessary to elucidate the saturation characteristics and mechanism with wider range of the excitation power.

Shown in Fig. 4 are the averaged values of the spectral noise amplitude without the terahertz waves, as shown by the dotted curves in Fig. 1(c), as a function of the excitation power for various combinations of L_G and D_S. The average

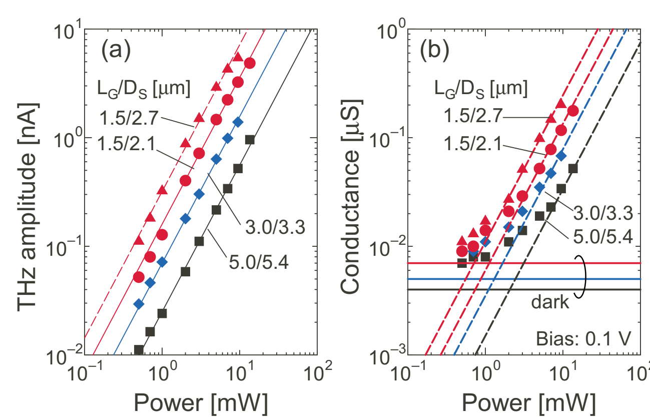

FIG. 3. (Color online) Incident power dependence of the (a) peak-to-peak amplitude in the time domain traces and (b) the conductance of the antenna. The lines represent the dependence of $P^{1.35}$ for the probe power P.

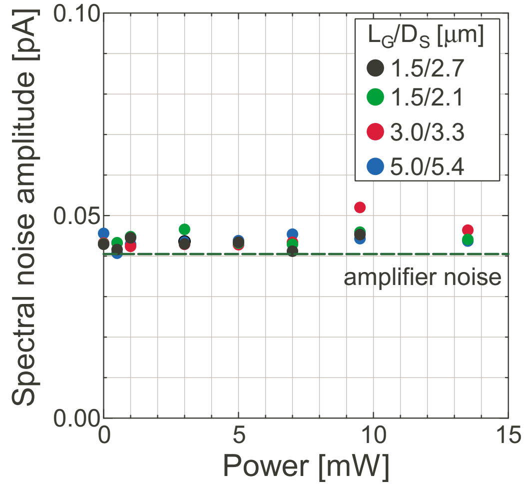

FIG. 4. (Color online) Averaged values of the noise spectra observed without terahertz waves as a function of the incident power on the detector antenna. The dashed line indicates the value of the amplifier noise obtained without the antenna.

was taken over the frequency range shown in the figure, omitting the zero frequency value. The noise level does not depend on the excitation power, the gap length, or the spot size. Moreover, the values are very close to the amplifier noise obtained without the antenna (open-circuited input) indicated by the dashed line in the figure, suggesting that the noise level of the detection system is dominated by the amplifier noise. In other words, the noise of the detector PCAs is very low corresponding to the low conductance even at the highest excitation in this measurement, which is a big benefit in using LTG GaAs as the photoconductive material.

In conclusion, we have demonstrated that the use of reduced spot size and an appropriately shortened gap of the PCA gives a meaningful enhancement of the terahertz signal detected by the PCA on the LTG GaAs for the 1560 nm excitation at a moderate incident power (pulse energy) of 9.5 mW (0.2 nJ). Moreover, it was found that the noise of the PCA does not increase with the increase of the incident power. As a result, the peak-to-noise ratio higher than 50 dB was obtained with a lock-in time constant of 10 ms. Further improvement of the performance would be possible by the increase of the incident power and/or the use of anti- and high-reflection coating on the substrate as well as the optimization of the gap length and the spot size.

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