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Ultrabroadband terahertz field detection by photoconductive antennas based on multi-energy arsenic-ion-implanted GaAs and semi-insulating GaAs

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The photoconductive antennas based on multi-energy arsenic-ion-implanted GaAs and semi-insulating GaAs are demonstrated to have a useful bandwidth beyond 20 THz for a gating laser pulse width of 15 fs. The bandwidth and signal-to-noise ratio are compared with those of reference photoconductive antennas based on low-temperature grown GaAs. © 2003 American Institute of Physics. [DOI: 10.1063/1.1604191]

Terahertz (THz) time-domain spectroscopy (THz-TDS) based on generation of pulsed THz radiation and its time-domain sampling detection by short laser pulses (in pump-probe scheme) are now widely used as a spectroscopic technique in mm and sub-mm wavelength region. At present, there are two commonly used schemes for generation and detection of THz radiation with femtosecond laser excitation: One is the use of photoconductive (PC) antennas and the other is the use of electro-optic crystals. The useful bandwidth in the THz-TDS with PC antennas has been typically limited within 3 THz (100 cm^{-1}). On the other hand, with the use of thin electro-optic crystals and very short laser pulses less than 20 fs, the spectrum distribution can be extended beyond 30 THz.^{1,2} The limited bandwidth of PC antennas was explained by the finite carrier lifetime or the momentum relaxation time of the carriers in the PC substrates.

However, recently, Kono, Tani, and Sakai^{3,4} found that PC antennas based on low-temperature grown GaAs (LT-GaAs) are also able to detect ultrabroadband THz radiation with the use of an appropriate optical setup. They reported the detectable spectral distribution was extended up to 60 THz by using short laser pulses less than 20 fs and a collinear geometry for THz beam and probe beam, unlike the commonly used anti-collinear geometry with the use of Si substrate lens.⁵ The fast response of the PC antennas has been explained by the fast rise of photoconductivity determined by the laser pulse width, while the photoconductive decay is determined by the carrier lifetime, which is much longer than the observed THz field oscillations. However, it was not clear how the photoconductive material properties affect the detection efficiency and bandwidth of PC antennas at such high frequencies. LT-GaAs grown by molecular beam epitaxy process has properties suitable for the PC antenna sub-

strate, that is, high resistivity, short carrier lifetime and relatively good carrier mobility. However, it is not an easy task to fabricate good quality LT-GaAs epitaxial film because optimization of the growth parameters, such as the growth temperature, is required. Arsenic-ion-implanted GaAs (GaAs: As⁺)⁶ exhibits structural, electrical, and ultrafast optoelectronic characteristics strikingly similar to those of LT-GaAs,⁷ and is expected to work as an efficient PC substrate as LT-GaAs. A semi-insulating (SI) GaAs bulk substrate has a good carrier mobility ($> 3000 \text{ cm}^2/\text{V/s}$), a high dark resistivity ($\sim 10^7 \Omega \text{ cm}$) and a long carrier lifetime ($> 100 \text{ ps}$). It was demonstrated that SI-GaAs can be used as the PC antenna substrate for detection of relatively low frequency THz radiation ($\sim 3 \text{ THz}$),⁸ although the noise level was significantly high compared to that with LT-GaAs substrate.

In this letter, we investigated the effect of substrate properties in the PC detection of ultrabroadband THz radiation by comparing the efficiency and bandwidth of PC antennas made with semi-insulating (SI) GaAs, LT-GaAs, and As-ion implanted GaAs. Since these PC materials have different carrier lifetimes and mobilities, the PC antennas based on these materials were expected to show different detection efficiency and bandwidth.

The GaAs: As⁺ substrate was prepared by implanting the semi-insulating (SI) GaAs substrate with arsenic ions at total doses of $10^{16} \text{ ions/cm}^2$ with multiple energies of 50, 100, and 200 keV. This was followed by furnace annealing at 600 °C for 30 min. The ion implantation depth was estimated to be about 100 nm by secondary ion mass spectroscopy measurement. The LT-GaAs was grown at a substrate temperature of 250 °C by molecular beam epitaxy and annealed at 600 °C for 5 min after growth. The carrier lifetimes of GaAs:As⁺ and LT-GaAs were all estimated to be around 1–2

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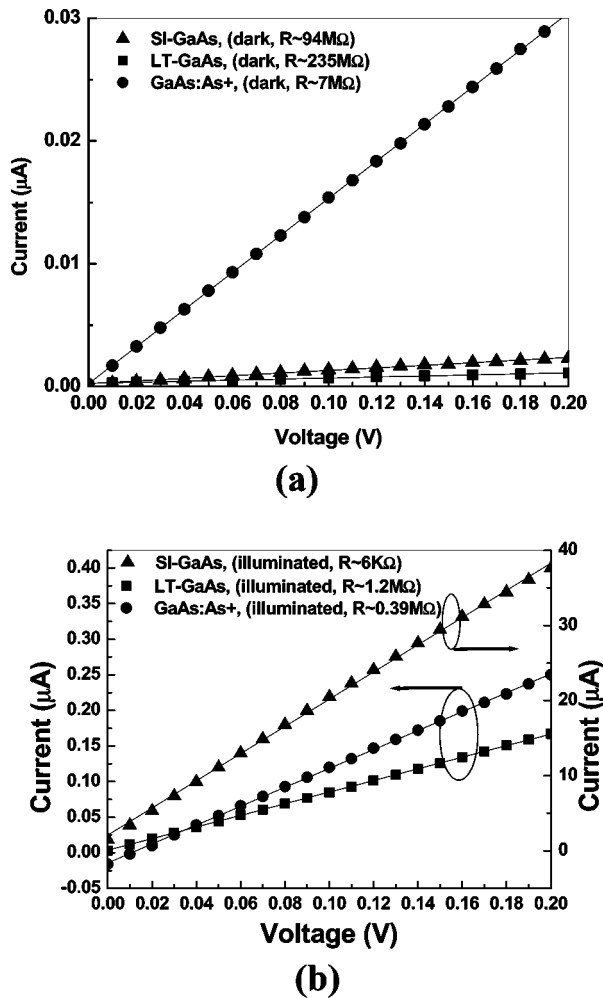


FIG. 1. Current–voltage (I – V) measurements (a) without and (b) with laser irradiation for GaAs:As⁺ (circle dot), SI-GaAs (triangular dot) and LT-GaAs (square dot) PC gap (5 μm) antennas near zero bias region. The resistance (R) estimated from the slope is indicated in each diagram.

ps by a transient photoreflectance measurement. A microstripline dipole antenna with 30 μm dipole length and a 5 μm PC gap in the center was fabricated on each PC substrate. A mode-locked Ti: sapphire laser, whose pulse width was 15 fs (the spectral width was 95 nm~47 THz), repetition rate 75 MHz, average output power 400 mW, a center wavelength of 800 nm, was used to generate broadband THz radiation from an electro-optic emitter and to gate the PC antenna detector. The experimental setup of the collinear PC detection system,³ which is similar to that reported in Ref. 3, was used. The average pump laser power was 150 mW after an optical chopper. 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 (f) of 50 mm to generate broadband THz radiation by the optical rectification effect. THz beam emitted from the ZnTe emitter was then collimated and focused onto the PC antenna by a pair of off-axis parabolic mirrors ($f=50$ mm). The gating laser power onto the detector was about 23 mW.

Figure 1 shows the current–voltage (I – V) measurement (a) without and (b) with the laser excitation (23 mW) for the GaAs:As⁺, LT-GaAs and SI-GaAs PC gap (5 μm) in a weak bias region. SI-GaAs and LT-GaAs PC gaps show lower dark

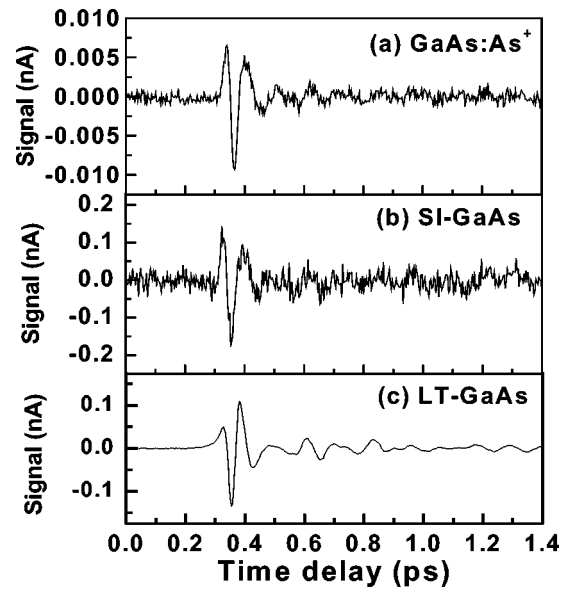


FIG. 2. Time-resolved THz radiation wave forms detected by PC antenna based on (a) GaAs:As⁺, (b) SI-GaAs and (c) LT-GaAs. The emitter was a 10- μm -thick (110) ZnTe crystal.

current. The resistance of LT-GaAs, GaAs:As⁺ and SI-GaAs PC gaps decreased to about 1.2 M Ω , 0.4 M Ω , and 6K Ω , respectively, by the laser irradiation. The significant decrease from the high dark resistance (~ 100 M Ω) to the low photoconductive resistance (6 k Ω) in the SI-GaAs gap indicates a large PC gain, which is attributed to the long carrier lifetime. The LT-GaAs gap showed the highest dark resistance. However, its photoconductive resistance was also high (low PC gain), which is attributed to the short carrier lifetime (~ 1 ps). On the other hand, GaAs:As⁺ showed the lowest dark resistance, while it showed slightly lower PC resistance (higher PC gain) than that of LT-GaAs (about one third of LT-GaAs). The lower PC resistance of GaAs:As⁺ compared to that of LT-GaAs is attributed to the slightly longer carrier lifetime (~ 2 ps) and a contribution from the nonion-implanted SI-GaAs substrate, which has a much lower photoconductive resistance than the As⁺-ion implanted layer.

There we observed significant stray currents in all antennas at the zero bias condition, which may contribute to the noise in THz signal detection; The stray current from SI-GaAs, GaAs:As⁺ and LT-GaAs was about 1.5 μA , 16, and 3 nA, respectively, at the gating power of 23 mW. The origin of the stray currents seems to be the asymmetric Schottky behavior at the metal-semiconductor contact. For dark I – V dependence, such Schottky characteristic is difficult to observe because of relatively high resistivity of the substrate. On the other hand, when we photoexcite the gap with the laser, increasing the conductivity, the Schottky characteristics of the contact become more clear, as observed in the I – V dependence with 23 mW excitation of the PC gap, which showed nonzero crossing at the $V=0$ axis (the vertical axis). Therefore, the high noise level observed in GaAs:As⁺ antenna is attributed to the asymmetric Schottky characteristics of the metal-semiconductor contacts in the photoexcited condition.

Figure 2 shows the signal wave forms detected by the (a) GaAs:As⁺, (b) SI-GaAs and (c) LT-GaAs PC antennas for

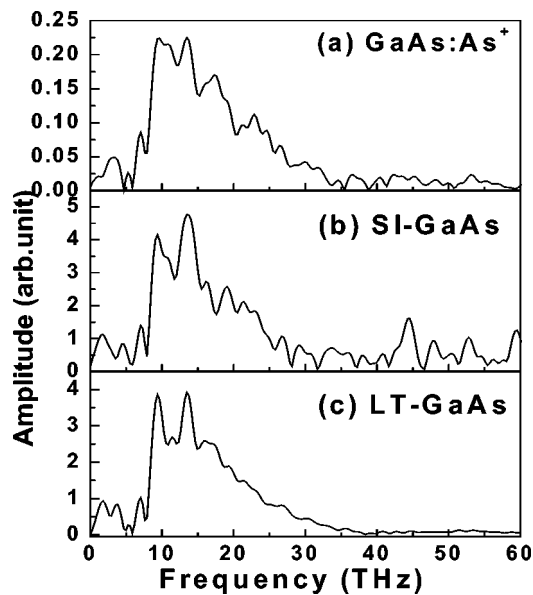


FIG. 3. Fourier transformed amplitude spectra of the PC-detected THz wave forms shown in Fig. 2.

THz radiation generated from the ZnTe emitter. THz wave form detected with the SI-GaAs antenna was averaged for three sequential scanning of the delay stage with a lock-in amplifier time constant of 0.3 s, while for the other PC antennas the scanning was only once. The detected peak signal current from GaAs:As⁺, SI GaAs and LT-GaAs PC antennas was 0.02, 0.3, and 0.24 nA, respectively. The signal to noise ratio (SNR) was estimated to be about 20, <10 and 100, respectively. The signal current detected with the GaAs:As⁺ PC antenna was lower than the other two types of PC antennas by one order, while the noise level was comparable to that of the LT-GaAs PC antenna. The low signal in the GaAs:As⁺ PC antenna is attributed to the insufficient thickness of the arsenic ion-implanted layer, which was only 10% of the absorption depth ($\sim 1 \mu\text{m}$) at the excitation laser wavelength; most of the carriers excited in SI-GaAs substrate beneath the ion-implanted layer could not contribute to the signal since after the photoconductive decay in As⁺-ion-implanted layer, the long-lived carriers in nonion-implanted SI-GaAs are blocked to flow into the antenna contact by the insulating layer. The SNR of SI-GaAs PC antenna was lowest, although the signal current level was the highest. The low SNR of SI-GaAs PC antenna is attributed to the large current noise originating from the long-lived photoexcited carriers (lifetime > 100 ps), while the other two have carrier lifetimes of 1–2 ps.

Figure 3 shows Fourier transformed amplitude spectra of

the THz wave forms shown in Fig. 2. The spectrum profiles are almost the same for the three cases. The high frequency end of the spectral distribution is extending to about 30 THz. The end of the spectral distribution above the noise floor was estimated to be 32 and 24 THz for GaAs:As⁺ and SI-GaAs PC antenna, respectively (40 THz for LT-GaAs PC antenna), which are the highest frequencies reported so far for the same kind of PC antennas. The spectral bandwidth was limited by the cutoff frequency (~ 40 THz) due to the phase mismatch between (the) THz radiation and pump laser pulse in the 10- μm -thick ZnTe emitter.³

It was reported that the main contribution to the noise in a PC detector is the Johnson noise (or thermal noise in resistance) and the laser shot noise.⁸ The Johnson noise in current 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. The photoconductive resistance is inversely proportional to the conductivity, σ , which in turn is proportional to product of mobility, μ , and carrier life time, τ . As a result, the noise level is proportional to the square root of the product of carrier lifetime and mobility: $I_{\text{noise}} \propto 1/\sqrt{R} \propto \sqrt{\sigma} \propto \sqrt{\mu\tau}$. The similarity between the spectra obtained with the three types of PC antennas indicates that neither the carrier lifetime nor the mobility (the carrier momentum relaxation time, in other words) are critical parameters for the detection bandwidth of the PC antenna, although these material parameters determine the efficiency and noise properties of the PC antennas.

In summary, ultrabroadband detection of THz radiation (~ 30 THz) by GaAs:As⁺ and SI-GaAs PC antennas was demonstrated. Their efficiency and bandwidth were compared with those of a reference LT-GaAs PC antenna. Although the SNR with GaAs:As⁺ PC antenna was lower than that of LT-GaAs PC antenna, it is possible to improve the efficiency by increasing the ion-implanted layer thickness. SI-GaAs PC antenna showed poor SNR due to a large noise originating from the long-lived photocarriers.

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