AIP | Applied Physics Letters

Detection of terahertz radiation with low-temperature-grown GaAs-based photoconductive antenna using 1.55 μm probe

Masahiko Tani, Kwang-Su Lee, and X.-C. Zhang

Citation: Appl. Phys. Lett. **77**, 1396 (2000); doi: 10.1063/1.1289914
View online: http://dx.doi.org/10.1063/1.1289914
View Table of Contents: http://apl.aip.org/resource/1/APPLAB/v77/i9
Published by the AIP Publishing LLC.

APPLIED PHYSICS LETTERS VOLUME 77, NUMBER 9 28 AUGUST 2000

Detection of terahertz radiation with low-temperature-grown GaAs-based photoconductive antenna using 1.55 μm probe

Masahiko Tani,[a] Kwang-Su Lee, and X.-C. Zhang
Department of Physics, Applied Physics and Astronomy, Rensselaer Polytechnic Institute, Troy, New York 12180-3590

(Received 7 February 2000; accepted for publication 28 June 2000)

THz radiation is detected by a low-temperature-grown GaAs (LT-GaAs) photoconductive antenna probed with a 1.55 μm probe laser. The detection efficiency is found to be approximately 10% of that obtained with a 780 nm probe. From the nonquadratic dependence of photoconductivity on laser intensity, two-step photoabsorption mediated by midgap states in LT-GaAs is suggested, instead of the two-photon absorption, as the primary process for the photoconductivity. © *2000 American Institute of Physics.* [S0003-6951(00)01335-8]

Generation and detection of terahertz (THz) radiation using a photoconductive (PC) antenna triggered by ultrashort optical pulses has been studied extensively for the last decade. Such a THz system using PC antennas enables us to measure time-domain amplitude wave forms of the THz radiation and provides a powerful method to investigate optical properties or dielectric responses of materials in the THz frequency range. Low-temperature-grown GaAs (LT-GaAs) has been the most widely used material for the PC emitter and detector because of its unique properties, such as the ultrashort carrier lifetime (<1 ps), large resistivity ($\sim 10^7\ \Omega$ cm), and relatively good carrier mobility ($\sim$200 cm^2/V/s).

For optical communication using the lossless 1.55 μm wavelength window, good progress has been made in pushing the limit of fast optoelectronic devices toward the terahertz regime. Unfortunately, GaAs as a commonly used material is usually not sensitive at 1.55 μm wavelength because the optical band gap is 1.43 eV at room temperature, corresponding to a wavelength of 867 nm. On the other hand, narrow-gap semiconductors, such as InGaAs[1] and Ge[2] have been used as the ultrafast PC material, aiming for the communication wavelength operation. However, the efforts on these narrow-gap materials have not been as successful as in the case of LT-GaAs, due mainly to the low dark resistivity, which is inevitable for narrow band gap semiconductors. High resistivity is important not only for performance of the PC emitter (the efficiency of a PC emitter increases with the bias electric field and is limited by the breakdown field of the PC antenna), but also for the PC detector because the noise due to thermal carriers (Johnson noise) in the signal current of a PC antenna is inversely proportional to the dark resistivity.[3] The high resistivity of LT-GaAs originates from the extremely high density of defects due to excess As incorporated during the low-temperature-growth, and/or the high density of As precipitates, which is formed after annealing.

Recently, generation and detection of an electrical pulse on a LT-GaAs photoconductive transmission line with 1.55 μm laser pulses was reported by Erlig *et al.*[4] They used the double sliding contact structure for the device and measured subpicosecond electrical pulses. Their result showed that LT-GaAs has a photoconductivity even at 1.55 μm, for which they attributed the origin to two-photon absorption.

In this letter, we report the results of a LT-GaAs-based photoconductive dipole antenna probed for THz wave detection with 1.55 μm optical pulses. It is found that the photoconductivity or the detection efficiency is nearly 10% of that obtained with 780 nm light. From the nonquadratic excitation intensity dependence of the photoconductivity at 1.55 μm, we suggest that the two-step photon absorption mediated by midgap states, formed by the excess As (1%–2%) in LT-GaAs, contribute to the photoconductivity at relatively low excitation power (<5 mW) rather than the two-photon absorption. It is also suggested that the direct excitation of electrons from the midgap states and As precipitates has nontrivial contribution to the photoconductivity in LT-GaAs.

We use a mode-locked fiber laser (IMRA Femtolite), with output at both the 1.55 μm fundamental and 780 nm second harmonic generated by periodically poled lithium niobate as the optical light source. The pulse width and repetition rate are $\sim$150 fs and 48 MHz, respectively. The emitter antenna consists of two parallel 10-μm-wide metal strip lines separated by 100 μm on an LT-GaAs substrate. This structure was biased with 160 V (dc) and pumped by the 780 nm beam separated from the 1.55 μm fundamental beam. The pump beam was modulated by a mechanical chopper at 1.7 kHz and focused on the emitter antenna by a lens. The detector antenna was a 50-μm-long Grischowsky-type dipole antenna with a 5 μm gap fabricated on a LT-GaAs/semi-insulating-GaAs substrate. The thickness of the LT-GaAs layer was 2 μm. The probe beam was focused by using an objective lens with 20× magnification.

Figure 1(a) shows the THz radiation wave form obtained with 780 nm pump (20 mW) and 780 nm probe (6 mW) as the reference data. The peak signal in the detector is 1.8 nA, and the signal-to-noise ratio (SNR) estimated from the ratio of the peak signal to the noise floor is about 2000. Figure 1(b) shows the THz wave form obtained with 780 nm pump (12 mW) and 1.55 μm probe (5 mW). In this case the residual second harmonic generation beam and other higher harmonics are rejected by inserting a 1.5-mm-thick silicon plate into the path of the probe beam. The peak signal amplitude is 80 pA with a SNR of 160. By assuming that the

---

[a] Author to whom correspondence should be addressed; electronic mail: tani@crl.go.jp

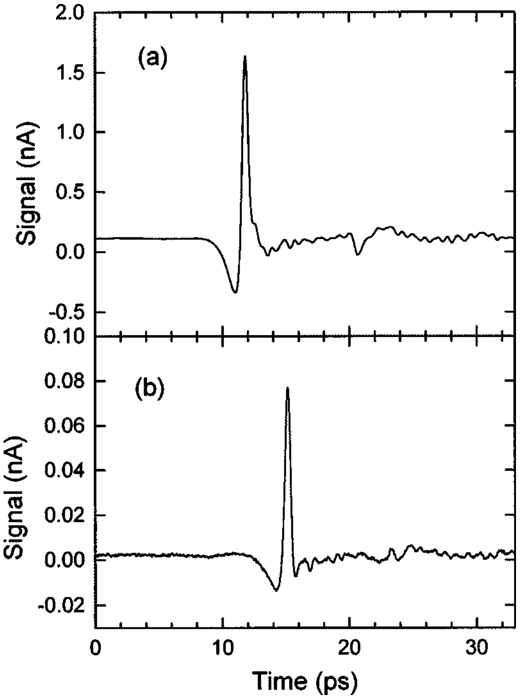

FIG. 1. Temporal wave forms of THz radiation detected by LT-GaAs PC antenna probed with: (a) 780 nm, 6 mW laser pulses; and (b) 1.55 μm, 5 mW laser pulses.

signal is proportional to the intensity of the pump and probe beams, we estimate the detector sensitivity with the 1.55 μm probe to be 9% of that obtained with the 780 nm probe. The estimated reduction in SNR for the same pump and probe power is about 1/6 (17%) of that with a 780 nm probe. The weaker reduction in SNR than in signal amplitude can be explained by the noise characteristics of the PC antenna: Since the noise due to photoexcited carriers also decreases in proportion to the square root of the current in the photoconductive antenna, while the signal amplitude decrease linearly with the current, the SNR decreases in proportion to the square root of the current or carrier density in the detector.[3] The expected SNR from this square-root law for the 1.55 μm probe is 30%$(=\sqrt{0.09}\times 100\%)$ of that for the 780 nm probe.

The observed sensitivity of the LT-GaAs PC antenna for the 1.55 μm probe is unexpectedly high if we consider only (i) the two-photon absorption process as the origin of the photoconductivity. There are several other possibilities for the photoconductivity in LT-GaAs at 1.55 μm: (ii) the two-step photoabsorption mediated by the midgap states, (iii) the excitation of trapped electron from midgap states to conduction band, and (iv) the excitation of trapped electrons in As precipitates to the surrounding LT-GaAs (the activation energy is about 0.7 eV).[4] It is expected that the two-photon absorption shows quadratic dependence on excitation intensity, while the last two single-step processes [(iii) and (iv)] show a linear dependence. The two-step absorption mediated by the midgap states is expected to show a nonlinear but nonquadratic dependence. In order to investigate the origin of the photoconductivity in LT-GaAs we measure the intensity dependence of the photocurrent in the PC detector (5 μm gap) with 1.55 μm laser pulse illumination under a dc bias (34 V). The result is shown in Fig. 2. The observed current consists of the dark current and the photocurrent. If the photocurrent comes from two-photon absorption alone, then it should be proportional to the square of the laser power, and the total current can be described as $J=Ap^2+J_{\mathrm{dark}}$, where J is total current, p laser power, A a constant proportional to the two-photon absorption coefficient, and J_{dark} dark current. However, the quadratic equation described above does not fit the observed current data at all. This suggests that the primary mechanism of photoconductivity is not the two-photon absorption at this level of excitation intensity, although it may contribute more at higher intensity.[5]

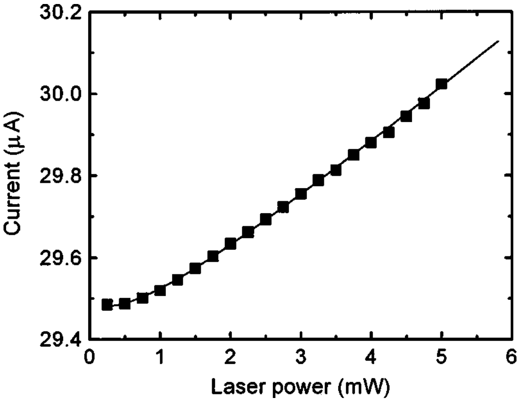

FIG. 2. Photocurrent vs laser power in 5 μm gap LT-GaAs. Bias voltage is 34 V.

Because the intensity dependence of the photoconductivity is close to linear but not completely linear, especially at low intensities, the excitation of trapped electrons from midgap states and As precipitates alone cannot explain the observed dependence. Therefore a two-step photoabsorption mechanism should be considered. To understand the property of the two-step absorption, a rate-equation model for the excitation and relaxation of electrons is developed, including the contributions from midgap states in LT-GaAs. LT-GaAs has a high density of EL2-like defects $(\sim 10^{20}/\mathrm{cm}^3)$[6] which lead to the formation of midgap states. The transition energy from valence band to midgap state is reported to be about 0.8 eV ($\sim$1.55 μm) in several published studies.[7] The band diagram and transition processes are illustrated in Fig. 3. We assume that the transitions occur from valence band to midgap states, and then from midgap states to upper conduction band states by 1.55 μm laser excitation—a two-step photo-

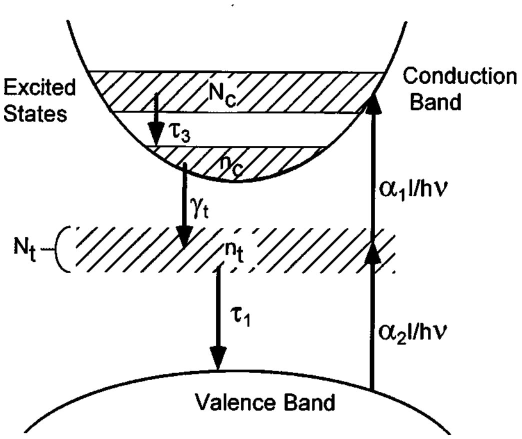

FIG. 3. Band diagram of LT-GaAs showing the excitation and decay processes in the rate equation model.

absorption. The decay processes occur from upper conduction band to lower conduction band (via longitudinal optical phonon emission), from lower conduction band to midgap states (trapping), and from midgap states to valence band (recombination). Based on our assumption, the rate equations for these states can be constructed as follows:

$$\frac{dN_c}{dt}=\frac{\alpha_1 I}{\hbar\omega}f_t-\frac{N_c}{\tau_3}, \tag{1}$$

$$\frac{dn_c}{dt}=\frac{N_c}{\tau_3}-\gamma_t n_c(1-f_t), \tag{2}$$

$$\frac{dn_t}{dt}=\frac{\alpha_2 I}{\hbar\omega}(1-f_t)-\frac{n_t}{\tau_1}-\frac{N_t}{\tau_1}+\gamma_t n_c(1-f_t), \tag{3}$$

where N_c is the population density of the upper conduction band, n_c the population density of the lower conduction band, n_t the population density of trapped electrons in midgap states, α_1 and α_2 unsaturated absorption coefficients between midgap states and upper conduction band, and valence band, respectively, and $I(\omega)$ is the intensity of light incident on the photoconductive antenna at frequency ω. τ_3 is the decay time from the upper conduction band to lower conduction band, γ_t is the decay rate of electrons from lower conduction band to midgap state, and τ_1 is the decay time from midgap states to valence band. $f_t=n_t/N_t$ (N_t: the density of midgap states) is the fraction of the midgap states which are occupied. The factor $(1-f_t)$ was introduced in the above rate equations in order to take into account the saturation effect expected for an intense excitation.[8] For weak excitations the saturation factor is approximated as $(1-f_t)=1$, and then the rate equations reduce to a set of linear equations. By using the steady state approximation $dN_c/dt=dn_c/dt=dn_t/dt=0$, the population density of each state is obtained as follows:

$$n_t=\frac{\alpha_2 N_t I/I_0}{(\alpha_2-\alpha_1)(1+I/I_0)}, \tag{4}$$

$$N_c=\frac{\alpha_1\alpha_2\tau_3 N_t(I/I_0)^2}{(\alpha_2-\alpha_1)^2\tau_1(1+I/I_0)}, \tag{5}$$

$$n_c=\frac{\alpha_1\alpha_2 N_t(I/I_0)^2}{(\alpha_2-\alpha_1)^2\tau_1\gamma_t\left(1-\dfrac{\alpha_1 I/I_0}{\alpha_2-\alpha_1}\right)}, \tag{6}$$

$$\begin{aligned}N_{\text{net}}=N_c+n_c=&\frac{\alpha_1\alpha_2\tau_3 N_t(I/I_0)^2}{(\alpha_2-\alpha_1)^2\tau_1(1+I/I_0)}\\&+\frac{\alpha_1\alpha_2(I/I_0)^2}{(\alpha_2-\alpha_1)^2\tau_1\left(1-\dfrac{\alpha_1 I/I_0}{\alpha_2-\alpha_1}\right)},\end{aligned} \tag{7}$$

where $I_0=\hbar\omega N_t/(\alpha_2-\alpha_1)\tau_1$, which has a unit of light intensity (I/I_0 is then a normalized light intensity without unit), and N_{net} is the net population density of electrons in the conduction band of LT-GaAs. The photocurrent in the LT-GaAs photoconductive antenna is given by

$$J_{\text{photo}}=\int e\mu_c N_{\text{net}}E\,ds, \tag{8}$$

where e is the unit electron charge, μ_e is mobility, E is the bias field, and the integral is carried out over the cross section normal to the bias direction in the photoconductor under the laser illumination. The theoretical pump-power dependent function for the total current J is then given by

$$\begin{aligned}J(p)&=J_{\text{photo}}(p)+J_{\text{dark}}\\&=C_1\frac{p^2}{(1+p)}+C_2\frac{p^2}{(1-C_3P)}+C_4,\end{aligned} \tag{9}$$

where p is the laser power (mW) and C_1–C_4 are the constants given by Eqs. (7) and (8). This theoretical function was fitted to the experimental data and shown in Fig. 2 by a solid line ($C_1=0.2$, $C_2=1.2$, $C_3=20$, and $C_4=J_{\text{dark}}=29.48\,\mu\text{A}$). The good agreement between the fitted curve and the experimental result indicates that the photoconductivity in LT-GaAs is well explained by two-step photoabsorption. However, the contribution from the direct excitation of trapped electrons from the midgap states and from As precipitates cannot be disregarded, because of the near linear property of the intensity dependence of the photoconductivity. It is noteworthy that the photoconduction induced by the direct photoexcitation from the midgap states does not include the electron–hole recombination process and is monopolar for electrons. This suggests that the photoconductive response originating from this process is faster than those with the recombination process. To determine the contribution from each process more quantitatively, further investigations are required.

In summary, we have demonstrated the detection of THz radiation with an LT-GaAs PC antenna using 1.55 μm laser pulses as the probe. The detection efficiency was about 10% of that with 780 nm light. From nonquadratic dependence of the photoconductivity on laser intensity, we suggested the two-step photoabsorption mediated by the high-density midgap states in LT-GaAs is responsible for the photoconductivity at 1.55 μm. An equation for the two-step photoabsorption is deriveded from a set of rate equations including the midgap states. The theoretical curve fitting the data reproduced the dependence of photoconductivity on excitation intensity very well.

This work was supported by the Army Research Office and the National Science Foundation. M.T. acknowledges support from Japanese Science and Technology Corporation through the Oversea Research Fellowship.

[1] S. Gupta, J. F. Whitaker, and G. A. Mourou, IEEE J. Quantum Electron. **28**, 2464 (1992).

[2] N. Sekine, K. Hirakawa, F. Sogawa, Y. Arakawa, N. Usami, Y. Shiraki, and T. Katoda, Appl. Phys. Lett. **68**, 3419 (1996).

[3] M. Tani, K. Sakai, and H. Mimura, Jpn. J. Appl. Phys., Part 2 **36**, L1175 (1997).

[4] H. Erlig, S. Wang, T. Azfar, A. Udupa, H. R. Fetterman, and D. C. Streit, Electron. Lett. **35**, 173 (1999).

[5] D. T. McInturff, J. M. Woodall, A. C. Warren, N. Braslau, G. D. Pettit, P. D. Kirchner, and M. R. Melloch, Appl. Phys. Lett. **60**, 448 (1992).

[6] K. M. Yu, M. Kaminska, and Z. Liliental-Weber, J. Appl. Phys. **72**, 2850 (1992).

[7] See for example, P. W. Yu, G. D. Robinson, J. R. Sizelove, and C. E. Stutz, Phys. Rev. B **49**, 4689 (1994).

[8] T. S. Sosnowski, T. B. Norris, H. H. Wang, P. Greiner, J. F. Whitaker, and C. Y. Sung, Appl. Phys. Lett. **70**, 3245 (1997).