ISSN 1063-7397, Russian Microelectronics, 2017, Vol. 46, No. 6, pp. 408–413. © Pleiades Publishing, Ltd., 2017.
Original Russian Text © I.A. Glinskiy, R.A. Khabibullin, D.S. Ponomarev, 2017, published in Mikroelektronika, 2017, Vol. 46, No. 6.

Total Efficiency of the Optical-to-Terahertz Conversion in Photoconductive Antennas Based on LT-GaAs and $In_{0.38}Ga_{0.62}As$

I. A. Glinskiy[a, b, *], R. A. Khabibullin[a], and D. S. Ponomarev[a]
[a] *Institute of Ultra High Frequency Semiconductor Electronics of Russian Academy of Sciences, Moscow, Russia*
[b] *Moscow Technological University (MIREA), Moscow, Russia*
**e-mail: glinskiy.igor@yandex.ru*
Received April 10, 2017

Abstract—The total efficiency of the optical-terahertz conversion η_{total} in photoconductive antennas (PCAs) on the basis of different materials (LT-GaAs and $In_{0.38}Ga_{0.62}As$) under optical laser excitation at wavelengths of 800 and 1030 nm is studied. It is shown that the photoconductive material factor $\mu\tau^2$ has a significant impact on the magnitude of the THz photocurrent and the value of η_{total}. With the use of electromagnetic modeling, the processes of heat transfer are studied and the power of Joule heating in these PCAs is evaluated.

DOI: 10.1134/S1063739717060051

INTRODUCTION

Photoconductive antennas (PCAs) are among the most used sources of broadband terahertz (THz) radiation [1–3]. An PCA generates ultrashort THz pulses with a high peak power at room temperature and does not require the use of powerful lasers for optical pumping [4, 5]. This enables the use of PCAs in the systems of THz spectroscopy and imaging for the analysis of biological objects, harmful substances, and chronic diseases (e.g., skin cancer).

The principle of PCAs is based on the effect of the action of a femtosecond laser pulse on the photoconductive layer of the antenna, resulting in the generation of electron-hole pairs, which are separated and accelerated by the voltage applied to the antenna. This leads to an induced THz photocurrent.

A key feature of PCAs is the efficiency of the conversion of the laser radiation into the generated THz power or, in other words, the efficiency of the optical-THz conversion, which is determined by the parameters of the photoconductive material [6], as well as by the topology of the antenna [7]. Different approaches are used to increase the efficiency: extension of the active region of PCAs by multiplying the individual sources [8, 9], the use of plasmonic nanoantennas formed on the surface of the photoconductive layer [10], etc.

A record efficiency of the optical-THz conversion of ~7.5% at low optical pumping of 1.4 mW was achieved using three-dimensional plasmonic electrodes [11].

In this work we studied the total efficiency of the optical-THz conversion depending on the parameters of the photoconductive material (LT-GaAs and $In_{0.38}Ga_{0.62}As$) under laser pumping at 800 and 1030 nm. The induced THz photocurrent and total efficiency of the optical-THz conversion were analytically calculated for each of the studied PCAs. Using electromagnetic modeling and the finite element method, we calculated the current-voltage characteristics of the PCAs and estimated the power of Joule heating.

NUMERICAL CALCULATION OF THE TOTAL EFFICIENCY OF THE OPTICAL-TERAHERTZ CONVERSION

The THz photocurrent and the efficiency of the optical-THz conversion were calculated for the PCAs on the basis of LT-GaAs and $In_{0.38}Ga_{0.62}As$ photoconductors. Their design method and manufacturing technology have been described in detail in [12]. The structure of an PCA is shown schematically in Fig. 1.

According to [13] the total efficiency of the optical-THz conversion (η_{total}) is defined as

$$\eta_{total} = \eta_{LE}\eta_m\eta_r, \tag{1}$$

where η_{LE} is the optical-electric efficiency of an PCA, i.e., the ratio of the electric power induced in the antenna gap due to the THz photocurrent (P_E) to the power of the pump laser (P_L), η_m is the impedance matching, and η_r is the radiation efficiency of antenna.

Let us first consider how to determine η_{LE}. The induced THz photocurrent can be described by the expression [4]

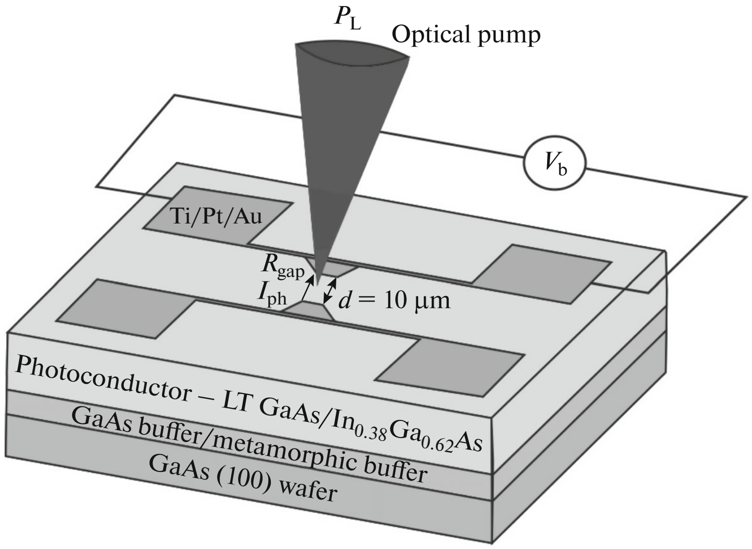

Fig. 1. Schematic structure of PCA based on LT-GaAs and $In_{0.38}Ga_{0.62}As$ with bow-tie topology.

$$I_{ph} = \frac{eV_b\mu_e\tau\eta_L P_L}{hf_L d^2}, \quad (2)$$

where e is the electron charge; V_b is the bias voltage; μ is the mobility of the charge carriers; τ is the lifetime of the charge carriers in the photoconductor; η_L is the efficiency of the laser irradiation; P_L is the average power of the optical radiation incident on the gap; h is the Planck constant; f_L is the frequency of the laser radiation; and d is the gap width between the electrodes of the antenna (see Fig. 1).

The gap resistance between the antenna's electrodes is given by [14]:

$$R_{gap} \approx \frac{hcf_R d^2}{\eta_L e\mu_e P_L \lambda_L}, \quad (3)$$

where c is the speed of light; f_R is the repetition rate of the femtosecond pulses; λ_L is the wavelength of the laser radiation (800 and 1030 nm, respectively).

Using Eqs. (2) and (3), we can obtain the expression for the electric power P_E and optoelectric efficiency of the η_{LE} antenna:

$$P_E = I_{ph}^2 R_{gap} \approx \left(\frac{eV_b\mu_e\tau\eta_L P_L}{hf_L d^2}\right)^2 \frac{hcf_R d^2}{\eta_L e\mu_e P_L\lambda_L} = \frac{eV_b^2\mu_e\tau^2\eta_L P_L cf_R}{hf_L^z d^2\lambda_L} = \frac{eV_b^2\mu_e\tau^2\eta_L P_L f_R}{hf_L d^2}. \quad (4)$$

Dividing P_E into P_L, we obtain an expression for η_{LE}:

$$\eta_{LE} = \frac{P_E}{P_L} \approx \frac{eV_b^2\mu_e\tau^2\eta_L f_R}{hf_L d^2}. \quad (5)$$

As seen from (5), the optical-electric efficiency of the PCA is directly proportional to the square of the supply voltage V_b^2 and to the photoconductive material factor $\mu\tau^2$. Thus, the lifetime of the photoexcited charge carriers in the photoconductor and the resistance have a decisive influence on the frequency parameters of the antenna.

The value of η_{LE} was determined using the following parameters of the femtosecond: the optical pumping power at $\lambda_L = 800$ nm ($f_L = 375$ THz) and 1030 nm ($f_L = 291$ THz) was 30 mW; the repetition rate of the optical pulses was 80 MHz; $\eta_L = 2/3$ at the gap width between the antenna electrodes of 10 microns. For the photoconductive material, the following values of the parameters were used: $\mu_{(LT\text{-}GaAs)} = 1000$ cm^2/V s, $\tau_{(LT\text{-}GaAs)} = 0.5$–$2.5$ ps [15], $\mu_{(In_{0.38}Ga_{0.62}As)} = 2000$ cm^2/V s, and $\tau_{(In_{0.38}Ga_{0.62}As)} = 5$–$10$ ps.

The value of η_r is defined as the ratio of the emitted THz power to the input pump power and depends on the radiation characteristics of the antenna, and in particular on the radiation direction and the degree of absorption of THz radiation in the GaAs substrate. The directivity factor and the shape of the radiation pattern in the far zone directly depend on the antenna's topology. Because the substrate material of the PCAs has a high dielectric constant ($\varepsilon_{GaAs} \approx 12.9$), at a large thickness of the substrate, the radiation efficiency falls sharply due to the generation of surface waves [16]. In the calculations, the radiation efficiency η_r was taken to be 80% [13].

Table 1. Efficiency of optical-THz conversion for PCAs based on LT-GaAs and $In_{0.38}Ga_{0.62}As$ at different pumping wavelengths

Optical pumping wavelength λ_L, nm	Photoconductive material	V_b, V	I_{ph}, mA	R_{gap}, Ohm	η_{total} (calculation)
800	LT-GaAs	20	0.27	5.98	1.35×10^{-5}
	$In_{0.38}Ga_{0.62}As$	10	2.67	2.99	2.62×10^{-4}
1030	$In_{0.38}Ga_{0.62}As$	10	3.44	2.32	2.76×10^{-4}

The impedance matching is the ratio of the input power received by the antenna (P_{in}) to the power supplied by the source (P_s), and in the case of PCA is given by

$$\eta_m = \frac{P_{in}}{P_s} = 1 - \left(\frac{Z_a - Z_s}{Z_a + Z_s}\right)^2, \qquad (6)$$

where Z_s is the impedance of the antenna source and Z_a is the antenna impedance.

Note that the impedance matching for the PCAs is a complicated task due to the pulsed nature of optical radiation. Because of the time-varying conductivity of the photoconductive material during optical pumping, the impedance of the antenna source also changes over time and depends on the regime of optical radiation (in particular, the duration and period of the femtosecond pulse).

The antenna's impedance Z_a, taking into account the substrate, was determined using the approximation $Z_a \approx Z_{free}/\varepsilon_r^{1/2}$, where Z_{free} is the antenna's impedance in free space (≈73 Ohms), ε_r is the dielectric constant (≈12.9 and ≈13.5 for LT-GaAs and $In_{0.38}Ga_{0.62}As$, respectively). The impedance of the antenna source corresponds to the resistance of the photoconductive layer in the gap between the antenna's electrodes and is determined by formula (3). Thus, for the LT-GaAs PCA $\eta_m \approx 0.703$ and for the $In_{0.38}Ga_{0.62}As$ PCA $\eta_m \approx 0.455$. The mismatch of the impedances is caused by the low resistance of the irradiated photoconductive material compared to the resistance of the antenna.

RESULTS AND DISCUSSION

Table 1 shows the results of the numerical calculation of the photocurrent I_{ph} and the total efficiency of the optical-THz conversion for the PCAs on the basis of LT-GaAs (pumping at λ_L = 800 nm) and $In_{0.38}Ga_{0.62}As$ (pumping at λ_L = 800 and 1030 nm).

As can be seen, at the same pumping wavelength of λ_L= 800 nm, the $In_{0.38}Ga_{0.62}As$ PCAs THz photocurrent is twice as high compared to the LT-GaAs PCA, and η_{total} increases by more than an order of magnitude. An increase in the wavelength to λ_L = 1030 nm (for the $In_{0.38}Ga_{0.62}As$-based PCA) leads to a 30% increase of I_{ph} but the conversion efficiency increases by only 5%. This is because as λ_L is increased, the impedance matching is reduced due to the decrease of the resistance of the gap.

Figure 2 shows the dependence of the total optical-THz conversion η_{total} on the width of the electrode gap d of the antenna for different pumping wavelengths. As can be seen, for the LT-GaAs-based PCAs, the decrease in d has almost no effect on the value of η_{total}, while for the $In_{0.38}Ga_{0.62}As$-based PCAs, η_{total} markedly increases with the decrease of the gap from 15 to 5 μm. This can be explained as follows. Since the charge carriers in $In_{0.38}Ga_{0.62}As$ have a small effective mass [17], they are accelerated by the applied electric field much faster, which reaches the maximum value as the gap is reduced. It is also worth noting that for both PCAs the electric field value at the minimum gap (d = 5 μm) is lower than the breakdown value for LT-GaAs and $In_{0.38}Ga_{0.62}As$.

The inset in Fig. 2 shows the dependence of η_{total} for the $In_{0.38}Ga_{0.62}As$ PCA on the photoconductive material factor $\mu\tau^2$ for two values of λ_L = 800 and 1030 nm. It is important to note that for a fixed V_b = 10 V, the total efficiency of the optical-THz conversion increases to a maximum of 4 times, even for the highest values of $\mu\tau^2$.

Figure 3 shows the calculated dependence of η_{total} on the value of the applied voltage V_b. It is seen that as V_b approaches the value of the threshold breakdown voltage V_{th} (V_{th} ~ 20 V for $In_{0.38}Ga_{0.62}As$ [12]), the antenna on the $In_{0.38}Ga_{0.62}As$ basis has a total efficiency that is higher by a factor of about 5 than the PCA on an LT-GaAs basis. Also, because $\mu\tau^2$ makes a stronger contribution to the conversion efficiency than V_b, $In_{0.38}Ga_{0.62}As$ is characterized by a sharp growth of η_{total} when V_b increases compared to LT-GaAs. It should be noted that at large values of V_b, the LT-GaAs antennas can compete in the magnitude of η_{total} with the $In_{0.38}Ga_{0.62}As$ antennas. However, this can cause a breakdown due to the Joule heat and an increase in the dark current [12, 18].

Additionally, to study the heat transfer processes in LT-GaAs and $In_{0.38}Ga_{0.62}As$ PCAs under the influence of a femtosecond laser pulse, we performed electromagnetic modeling by the finite element method implemented in the COMSOL Multiphysics software

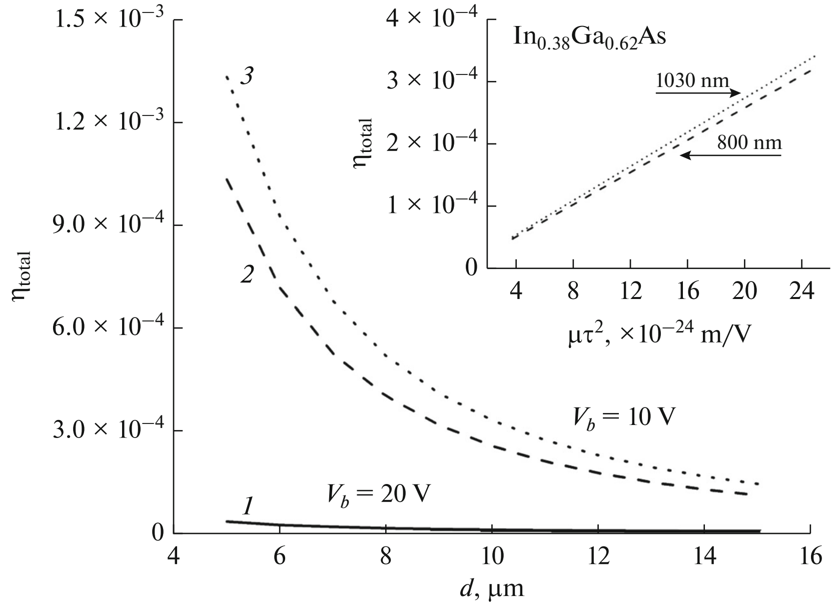

Fig. 2. Dependence of total efficiency of optical-THz conversion η_{total} on factor of photoconductive layer $\mu\tau^2$ for PCA on basis of LT-GaAs at (*1*) $\lambda_L = 800$ nm and for PCA on basis of $In_{0.38}Ga_{0.62}As$ at (*2*) $\lambda_L = 800$ nm and (*3*) 1030 nm.

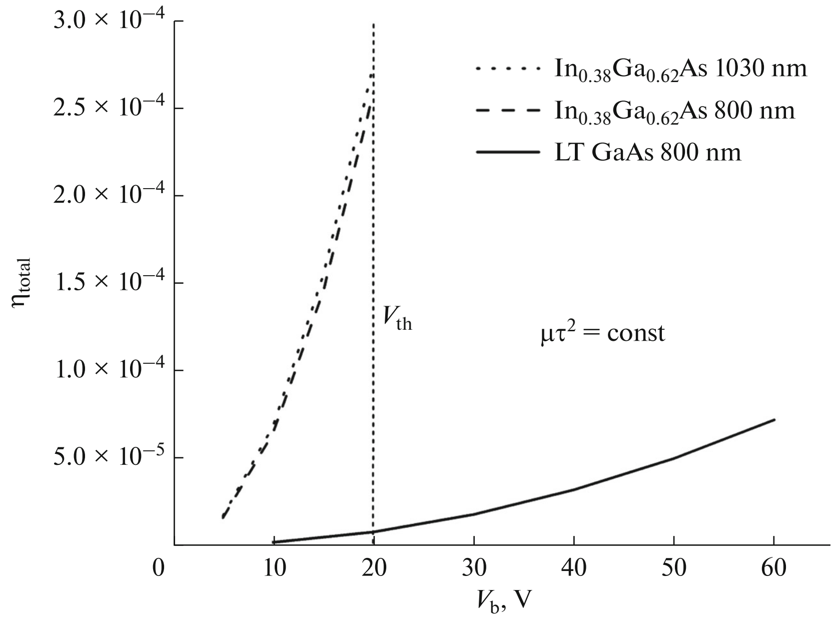

Fig. 3. Dependence of total efficiency of optical-THz conversion η_{total} on applied voltage (V_b) for PCAs based on LT-GaAs and $In_{0.38}Ga_{0.62}As$.

environment [19]. The PCA model was based on the experimental measurements of the current-voltage characteristics (CV) [12]. As can be seen from Figs. 4 and 5, the theoretical curve for the dark current I_{dark} (model) is closely correlated with the experimental dependence I_{dark} (exp.).

For the LT-GaAs-based antenna, the CV, taking into account the THz photocurrent ($I_{dark} + I_{ph}$), exhibits three distinct regions (Fig. 4): the first at $V_b \leq 9$ V corresponds to the linear dependence of the CV, where the influence of the dark current and photocurrent is small; the second region is from $V_b = 9$ to 16 V and is characterized by the release of the Joule heat P_H under the action of both currents [20]; the third region at $V_b \geq 16$ V is close to the breakdown of the antenna. It should be noted that the $In_{0.38}Ga_{0.62}As$ PCAs is characterized by a somewhat different CV. As can be seen from Fig. 5, at $V_b \sim 9$ V the magnitude of ($I_{dark} + I_{ph}$) is almost triple that for LT-GaAs. This is because the $In_{0.38}Ga_{0.62}As$ antennas are greatly affected by the dark

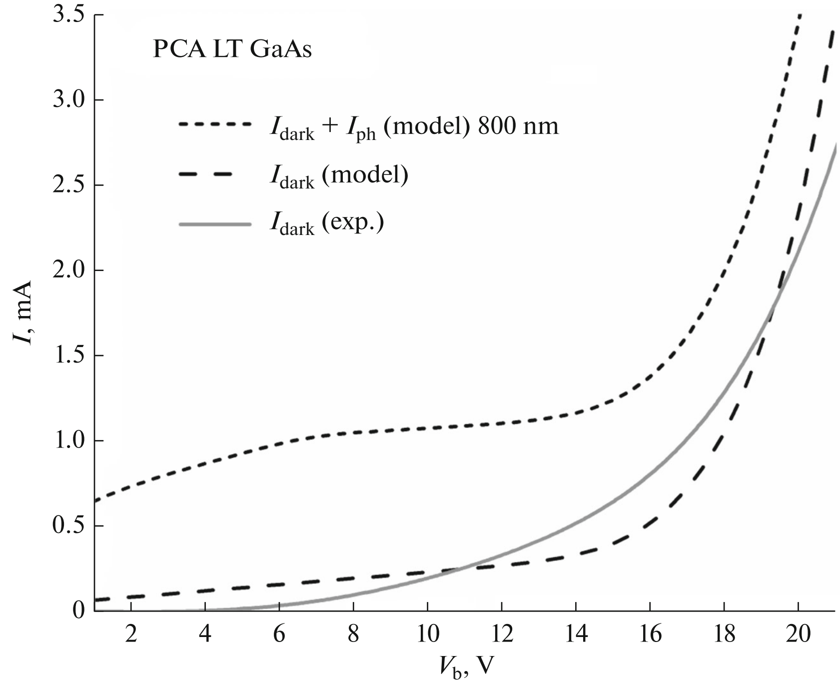

Fig. 4. Comparison of experimental and theoretical CV of dark current (I_{dark}) for LT-GaAs PCA taking into account influence of photo- and dark currents ($I_{dark} + I_{ph}$) under optical pumping at 800 nm.

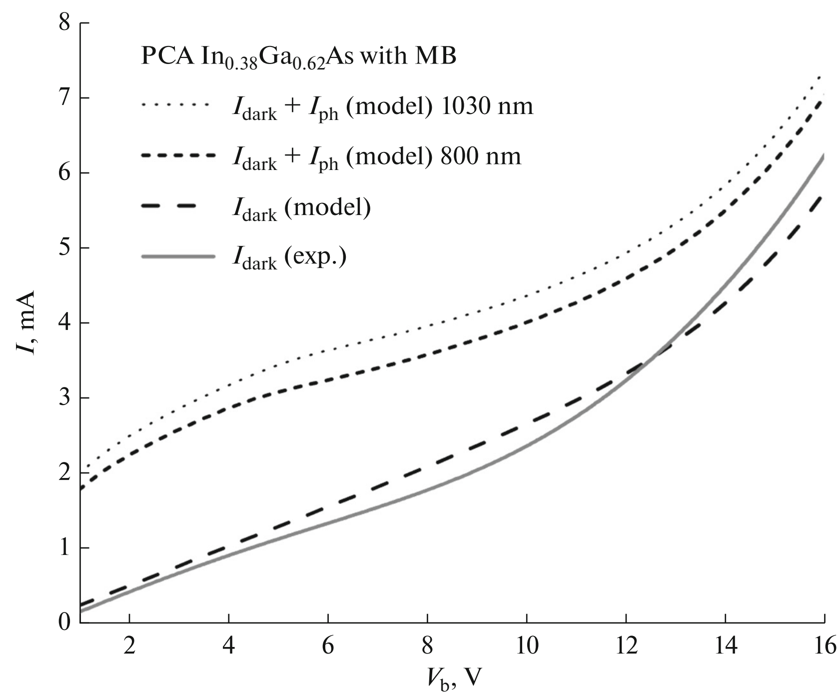

Fig. 5. Comparison of experimental and theoretical CV of dark current (I_{dark}) for $In_{0.38}Ga_{0.62}As$ PCA taking into account influence of photo- and dark currents ($I_{dark} + I_{ph}$) under optical pumping at 800 and 1030 nm.

current with increasing V_b due to the smaller band gap in $In_{0.38}Ga_{0.62}As$. For this reason, the second and third regions merge into one and the antenna can break down at $V_b \sim 12$ V. The typical calculated maximum value of the P_H, taking into account the photo- and dark currents, amounts to $P_H \sim 5.07 \times 10^{13}$ W/m^3 for the PCA ($\lambda_L = 800$ nm) at $V_b = 20$ V and $P_H \sim 8.22 \times 10^{13}$ W/m^3 ($\lambda_L = 800$ nm) and $P_H \sim 8.5 \times 10^{13}$ W/m^3 ($\lambda_L = 1030$ nm) for the $In_{0.38}Ga_{0.62}As$ PCA at $V_b = 10$ V. Thus, for the LT-GaAs-based PCA, the action of laser pumping leads to the P_H quadrupling and the $In_{0.38}Ga_{0.62}As$-based PCA more than doubling.

CONCLUSIONS

In this work we studied the total efficiency of the optical-terahertz conversion in photoconductive antennas based on LT-GaAs and $In_{0.38}Ga_{0.62}As$ under laser pumping at 800 and 1030 nm. It is shown that the photoconductive material factor $\mu\tau^2$ has a greater impact on the values of the THz photocurrent and η_{total} than the voltage applied to the antenna. Using electromagnetic modeling by the finite element method, it was shown that the current-voltage characteristics for LT-GaAs and $In_{0.38}Ga_{0.62}As$ PCAs are slightly different, due to the influence of the dark current and Joule heating.

ACKNOWLEDGMENTS

This work was supported by the Russian Science Foundation, grant 14-29-00277 (D.S. Ponomarev and R.A. Khabibullin calculated the THz photocurrent and efficiency of the total optical-THz conversion). Modeling in COMSOL was supported by the Russian Fund for Basic Research, grants 16-29-14029 ofi_m, 16-07-00187 A, and 16-29-03033 ofi_m.

REFERENCES

1. Burford, N.M. and El-Shenawee, M.O., Review of terahertz photoconductive antenna technology, *Opt. Eng.,* 2017, vol. 56, no. 1, p. 010901.
2. Yardimci, N.T. and Jarrahi, M., High sensitivity terahertz detection through plasmonic nano-antenna arrays, *Sci. Rep.,* 2017, vol. 7, p. 42667.
3. Ponomarev, D.S., Khabibullin, R.A., Yachmenev, A.E., Maltsev, P.P., Grekhov, M.M., Ilyakov, I.E., Shishkin, B.V., and Akhmedzhanov, R.A., Terahertz radiation in $In_{0.38}Ga_{0.62}As$ grown on a GaAs wafer with a metamorphic buffer layer under femtosecond laser excitation, *Semiconductors,* 2017, vol. 51, no. 4, pp. 509–514.
4. Smith, P.R., Auston, D.H., and Nuss, M.C., Subpicosecond photoconducting dipole antennas, *IEEE J. Quantum Electron.,* 1988, vol. 24, no. 2, pp. 255–260.
5. Ponomarev, D.S., Khabibullin, R.A., Yachmenev, A.E., Maltsev, P.P., Ilyakov, I.E., Shiskin, B.V., and Akhmedzhanov, R.A., Intensive terahertz radiation from $In_xGa_{1-x}As$ due to photo-dember effect, *IJHSES,* 2016, vol. 25, nos. 3–4, p. 1640023.
6. Liu, T.A., Tani, M., and Pan, C.L., THz radiation emission properties of multienergy arsenic-ion-implanted GaAs and semi-insulating GaAs based photoconductive antennas, *J. Appl. Phys.,* 2003, vol. 93, pp. 2996–3001.
7. Klos, M., Bartholdt, R., Klier, J., Lampin, J.-F., and Beigang, R., Photoconductive antennas based on low temperature grown GaAs on silicon substrates for broadband terahertz generation and detection, *Proc. of SPIE,* 2016, vol. 9747, p. 974712-1.
8. Preu, S., Mittendorff, M., Lu, H., Weber, H.B., Winnerl, S., and Gossard, A.C., 1550 nm ErAs:In(Al)GaAs large area photoconductive emitters, *Appl. Phys. Lett.,* 2012, vol. 101, p. 101105.
9. Beck, M., Schäfer, H., Klatt, G., Demsar, J., Winnerl, S., Helm, M., and Dekorsy, T., Impulsive terahertz radiation with high electric fields from an amplifier-driven large-area photoconductive antenna, *Opt. Express,* 2010, vol. 18, no. 9, pp. 9251–9257.
10. Chimot, N., Mangeney, J., Mounaix, P., Tondusson, M., Blary, K., and Lampin, J.F., Terahertz radiation generated and detected by Br^+-irradiated $In_{0.53}Ga_{0.47}As$ photoconductive antenna excited at 800 nm wavelength, *Appl. Phys. Lett.,* 2006, vol. 89, p. 083519.
11. Yang, S.-H., Hashemi, M.R., Berry, C.W., and Jarrahi, M., 7.5% optical-to-terahertz conversion efficiency offered by photoconductive emitters with three-dimensional plasmonic contact electrodes, *IEEE Trans. Tera. Sci. Technol.,* 2014, vol. 4, pp. 575–581.
12. Ponomarev, D.S., Khabibullin, R.A., Yachmenev, A.E., Pavlov, A.Yu., Slapovskii, D.N., Glinskiy, I.A., Lavrukhin, D.V., Ruban, O.A., and Mal'tsev, P.P., Electric and thermal properties of photoconductive antetta based on $In_xGa_{1-x}As$ ($x > 0.3$) with metamorphic buffer layer for terahertz radiation generation, *Semiconductors,* 2017, vol. 51, no. 9, pp. 1218–1223.
13. Huang, Y., Khiabani, N., Shen, Y., and Li, D., Terahertz photoconductive antenna efficiency, in *Proceedings of the International Workshop on Antenna Technology iWAT, Hong Kong, China, March 7–9, 2011,* pp. 152–156.
14. Ezdi, K., Islam, M.N., Reddy, Y., Jordens, C., Enders, A., and Koch, M., A numerical study of photoconductive dipole antennas: the real emission frequency and an improved antenna design, *Proc. SPIE,* 2006, vol. 6194, pp. 61940G-1–9.
15. Lavrukhin, D.V., Yachmenev, A.E., Bugaev, A.S., Galiev, G.B., Klimov, E.A., Khabibullin, R.A., Ponomarev, D.S., and Maltsev, P.P., Investigation of the optical properties of GaAs with δ-Si doping grown by molecular-beam epitaxy at low temperatures, *Semiconductors,* 2015, vol. 49, no. 7, pp. 911–914.
16. Shahvarpour, A., Melcon, A.A., and Caloz, C., Radiation efficiency issues in planar antennas on electrically thick substrates and solutions, *IEEE Trans. Anten. Propagat.,* 2013, vol. 61, no. 8, pp. 4013–4025.
17. Kulbachinskii, V.A., Yuzeeva, N.A., Galiev, G.B., Klimov, E.A., Vasil'evskii, I.S., Khabibullin, R.A., and Ponomarev, D.S., Electron effective masses in an InGaAs quantum well with InAs and GaAs inserts, *Semicond. Sci. Technol.,* 2012, vol. 27, no. 3, p. 035021.
18. Harmon, E.S., Melloch, M.R., Woodall, J.M., Nolte, D.D., Otsuka, N., and Chang, C.L., Carrier lifetime vs. anneal in low growth temperature GaAs, *Appl. Phys. Lett.,* 1993, vol. 63, no. 16, pp. 2248–2250.
19. Glinskii, I.A. and Zenchenko, N.V., Computer simulation of the heat distribution element for high-power microwave transistors, *Russ. Microelectron.,* 2015, vol. 44, no. 4, pp. 236–240.
20. Collier, C.M., Stirling, T.J., Hristovski, I.R., Krupa, J.D.A., and Holzman, J.F., Photoconductive terahertz generation from textured semiconductor materials, *Sci. Rep.,* 2016, vol. 6, p. 23185.

Translated by V. Alekseev