Terahertz photoconductive antenna with embedded electrodes: simulation and experiment

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Abstract. The paper presents the results of numerical simulation of a terahertz (THz) photoconductive antenna with embedded electrodes by the finite element method. The simulation results indicate the fact that the proposed THz antenna has a higher photocurrent than the conventional photoconductive antenna with conventional electrode contacts. Higher THz power can potentially be obtained using the proposed photoconductive antenna with embedded electrodes. The simulation results show that the electric field strength at the surface is higher for conventional PCA, however, the PCA depth with embedded contacts has a higher electric field strength. The simulation results show that the increase in the photocurrent is directly proportional to the thickness of the embedded contacts. The results of the performed experiments are consistent with the conclusions of the simulation.

1. Introduction

The development of efficient compact antennas for transmitting and receiving terahertz waves is urgent. Recently, works have been published, some of which are considered below, devoted to the creation of photoconductive antennas (PCA) that increase their efficiency due to a change in the mesa structure of contacts, as well as modeling of the electrophysical parameters of THz (PCA) depending on the type of contacts.

InGaAs / InAlAs photoconductive antennas emitting radiation at a wavelength of 1.5 μm have been improved by mesa-etching of the conducting layers [1]. Electrical side contacts were applied to the multilayer structure, and the layers are removed in areas that are only prone to parasitic dark currents. Consequently, photocurrents are increased 5 times, and parasitic dark currents are suppressed. The radiated terahertz power is increased by more than 5 times compared to conventional planar antennas, the sensitivity of the receiver is increased by 11 times. Overall, the mesastructured antenna outperforms previous planar systems by a factor of 27.5 in output signal amplitude.

A metal-semiconductor-metal (MSM) photodetector based on low-temperature GaAs with doped (that is, ohmic type) contacts have been manufactured and characterized [2]. Burn-in contacts optimize the distribution of the electric field within the structure of the photodetector, which leads to an increase in the sensitivity of the devices by up to 200% compared to conventional MSM detectors with standard Schottky-type metalized metallization made on an identical material.

Thus, in [3], a simulation of the PCA was carried out, where the substrate used is a low-temperature gallium arsenide LT-GaAs, with a hole mobility of 400 cm²/V * s and electron mobility of 8500 cm²/V
A linear dependence of the strength of the photocurrent excited by a picosecond laser pulse, PCA, on the bias voltage is observed. Comparative analysis of the photocurrent of an antenna with two-fold lower mobility of charge carriers showed a directly proportional dependence of the calculated theoretical values of the photocurrent on the bias voltage and a higher photocurrent for PCA with higher values of the mobility of charge carriers.

A photoconductive terahertz antenna based on a distributed Bragg reflector, nanoplasmonic gratings, and recessed electrodes was proposed in [4]. Using the finite element method and two-wave modeling, the influence of geometric parameters on the nonstationary photocurrent of the proposed photoconductive antenna is investigated. The nanoplasmonic structure reduces the reflection of laser light by up to 1.5% from the surface of low-temperature gallium arsenide, compared to 29% for a conventional photoconductive antenna. According to the results, a distributed Bragg reflector in combination with a nanoplasmonic grating and recessed electrodes leads to an increase in the photocurrent peak by 5265% compared to a conventional terahertz photoconductive antenna.

A THz PCA with a plasmon grating, a metal electrode height \( h = 100 \text{ nm} \), and an aspect ratio \( h / p = 0.5 \) (\( p \) is the period of the plasmon grating) was proposed in [5]. Higher power of generated THz radiation in a plasmon PCA, which is two orders of magnitude higher than in an equivalent PCA without a plasmon grating, has been experimentally demonstrated. This is due to a sharp increase in the electric field near the metal-semiconductor contact in the plasmon lattice, in connection with which a larger number of photoexcited current carriers reach the antenna contacts and contribute to the generation of THz radiation.

Thus, the efficiency of the PCA antenna can be increased in two ways: the first is the use of embedded contacts, the second is the use of nanoplasmonic gratings in the interelectrode gap.

The work aims to simulate the PCA of an antenna with embedded contacts, create a PCA with embedded electrodes, and compare the experimental data with the simulation results.

2. Simulation and experimental methods

2.1. Simulation

The model consists of two related studies - stages; first, the optical response is calculated in the frequency domain using the electromagnetic wave equation (1).

\[
\nabla \times \mu_r^{-1} (\nabla \times \mathbf{E}) - k_0^2 (\epsilon_r - \frac{j \sigma}{\omega \epsilon_0}) \mathbf{E} = 0
\]

The laser source is modeled as a focused monochromatic Gaussian beam at a wavelength of 800 nm. From here it is possible to calculate the Poynting vector and, as such, the photon absorption flux inside the PCA substrate. The advantage of including this step in the model is that the photon absorption flux in the PCA substrate is not uniform. Although uniform absorption approximations have been shown to work for traditional THz PCA, it is well known that plasmonic photoconductive devices have an extremely inhomogeneous distribution of the electric field, with most of the electromagnetic energy highly concentrated near the plasmonic structure [2].

The second study - the stage determines the dynamics of carriers due to the applied bias \( V \) and the optical generation rate of charge carriers \( U_{n,p} \). The peak generation of carriers is taken from the photon absorption flux calculated in the first stage, an optical study, and is approximated by a Gaussian time dependence. The temporal pulse width corresponds to the width of the femtosecond laser pulse (full width at the half-amplitude level is \( \approx 100 \text{ fs} \)). The equations governing the dynamics of these charge carriers in the semiconductor layer are the Poisson equation (2) and the carrier transport equations for electrons (3) and holes (4):

\[
\nabla \cdot (\epsilon_r \nabla V) = q(n - p + N_A - N_D)
\]
\[ \frac{\partial n}{\partial t} = -\frac{1}{q} \nabla J_n - U_n \]  
(3)

\[ \frac{\partial p}{\partial t} = \frac{1}{q} \nabla J_p - U_p \]  
(4)

Here \( n \) and \( p \) are the concentration of electrons and holes, \( N_a \) is the concentration of acceptors, \( N_p \) is donors, \( U_n = R_n + G_n \), where \( R_n \) is the rate of electron recombination, \( G_n \) is the rate of electron generation, \( U_p = R_p + G_p \), where \( R_p \) is the rate recombination of holes, \( G_p \) is the rate of generation of holes, \( J_n, p \) is the current density of electrons/holes. The current density is a function of the electron/hole concentration, material properties, and the applied potential \( V \). Equations (2-4) are then directly related through \( V, n, \) and \( p \), while equation (1) defines the spatial distribution \( U_n, p \) which depends only on time.

To check the correctness of the calculations, a simulation of a static electric field was carried out for two copper plates with a distance between them of 100 \( \mu m \) with a voltage between the plates of 2 V, shown in the figure. It can be seen that the lines of force of the electric field, marked with white arrows (the magnitude of the electric field depends on the thickness of these arrows) and the potential distribution correspond to the classical distribution of the field between two metal plates. Modeling was carried out by solving Maxwell's equations. Under static conditions, the electric potential \( V \) is determined by the ratio:

\[ E = -\Delta V \]  
(5)

Combining this equation with the defining relationship:

\[ D = \varepsilon_0 E + P \]  
(6)

between the electric displacement \( D \) and the electric field \( E \), one can represent Gauss's law as the following equation:

\[ -\nabla \cdot (\varepsilon_0 \nabla V - P) = \rho \]  
(7)

In this equation, the physical constant \( \varepsilon_0 \) (SI unit: F/m) is the dielectric constant of vacuum, \( P \) (SI unit: C/m\(^2\)) is the electric polarization vector, and \( \rho \) (SI unit: C/m\(^3\)) is the space charge density. This equation describes the electrostatic field in dielectric materials.

The proposed model was used to calculate the photocurrent as a function of the applied bias voltage. In fig. 2 shows a schematic diagram of photoconductive antenna structures and their corresponding dimensions for a conventional and proposed photoconductive antenna with fired electrodes, respectively. This is a model geometry, which differs in size from the real topology of contacts (The gap between the electrodes is 200 \( \mu m \), the thickness is 100 \( \mu m \), the height is 900 nm. In the model, the gap between the electrodes is 1 \( \mu m \), the thickness is 2.2 \( \mu m \) and the height is 80 nm), due to for problems in modeling at real dimensions (The Gaussian beam is blurred for such dimensions. The interelectrode gap becomes more than 2 orders of magnitude of the laser radiation wavelength). LT-GaAs was used as the substrate material, while gold was used as the electrode material. The simulated values of the electric field and photocurrent are constructed using a relatively constructed coordinate system, as shown in Fig. 2.

Simulation of the static electric field created by the bias voltage and applied to the electrodes for two antennas with different types of electrodes has been carried out. In Fig. 1 a, b, white lines show the lines of force of the static electric field. The thickness of these lines is directly proportional to the strength of the electric field. On the surface of the LT-GaAs semiconductor between the electrodes in an antenna with burn-in contacts (Fig. 1a), the concentration of thick lines is higher compared to conventional electrodes (Fig. 1b). Thus, the fired electrodes increase the area of the static electric field on the surface.
of the semiconductor between the electrodes in the antenna, created by the bias voltage in comparison with conventional electrodes.

![Figure 1](image1.png)

**Figure 1.** The lines of force of the static electric field and potential in the LT-GaAs antenna with conventional electrodes - a, with embedded electrodes - b.

A higher dc field in the near-surface layer of LT-GaAs leads to greater capture of photocarriers by electrodes, which increases the output photocurrent of the PCA.

![Figure 2](image2.png)

**Figure 2.** Schematic diagram of the structure of the simulated photoconductive antenna; (a) - conventional model, (b) - with embedded contacts.

Obviously, recessed electrodes can better collect photogenerated carriers, resulting in significantly increased sensitivity. Simply put, in devices with recessed electrodes, incident photons are absorbed in a larger volume of LT-GaAs, where a relatively uniform high electric field provides the most efficient collection of carriers.

Unlike microwave antennas, a photoconductive antenna in the millimeter range (wavelength range 1 mm - 30 μm) is powered by two different sources, namely from DC voltage and optical pumping. The finite element method, which combines the Maxwell wave equation with the Poisson drift-diffusion equations, allows one to calculate the density distribution of photogenerated carriers generated by a pump laser. Laser radiation characteristics: laser wavelength 800 nm, paraxial Gaussian beam with a beam radius of 800 nm. These data are necessary to calculate the distribution of the electric field inside the photoconductive device, photocurrent when a bias voltage is applied to the electrode.

### 2.2. Making experimental samples and measuring dark current

The PCA under study (samples 1 - 4) were fabricated on an epitaxial structure with an LT-GaAs film 1.2 μm thick. The LT-GaAs film was obtained by molecular beam epitaxy (MBE, Riber Compact 21
setup) at a temperature of 230 °C and a pressure ratio of As₄ molecules and Ga atoms equal to 19. After growth in the MBE chamber, the structure was annealed in an As flow at 580 °C. Flag-type PCA with metallization (Ni / Ge / Au / Ni / Au) was manufactured by standard methods of planar technology. The antenna geometry is shown in Figure 2. The width of the photoconductive gap between the PCA electrodes was 200 µm. For PCA №1, the contact embedded procedure was not performed, and for PCA №2-№4, a 2-minute contact firing was performed at a temperature of 410 °C. The thickness of the metalized contacts is 900 nm. The procedure for fabricating the PCA (samples 2 - 4) - growth, annealing of the LT-GaAs crystal, and embedding of contacts are identical.

![Figure 3. The geometry of electrodes manufactured by PCA](image)

The volt-ampere characteristics (I - V) of the antennas were measured using an EP6 handheld probe station (Cascade Microtech, USA) and an Agilent B1500A parametric analyzer (Agilent Technologies, USA). The bias voltage was of different polarities and varied from -50 V to 50 V. The I – V characteristics were measured in the dark and by irradiating the LT-GaAs working surface with a 150 W cold light source.

3. Results and Discussions

3.1. Experiment

Measurements of the dark current were carried out as a function of the bias voltage for a flag-type PCA with fired contacts at room temperature. The photocurrent was measured under irradiation of the LT-GaAs working surface with a 150 W cold light source. The results of measuring the dark current and photocurrent PCA are summarized in the table for the purpose of comparative analysis. The photocurrent was determined without laser irradiation of the interelectrode gap. The contact firing procedure was not performed over sample No. 1. The samples were annealed in a high-vacuum chamber at a temperature (Tann) of 580°C. The annealing time was 6 min in a vacuum of 10⁻⁷ Torr without stabilization by an arsenic flow, while the front side of the structure was tightly covered with a GaAs substrate. A sufficiently short annealing time was used to prevent a strong decrease in the density of arsenic clusters, as well as segregation of arsenic to the surface of the structure and its subsequent evaporation. Further, the contacts were fired in a high-vacuum chamber at a temperature of 410°C for 2 minutes in a vacuum with a pressure of 10⁻⁷ Torr.
Table 1. Conditions for growth, annealing, and annealing of contacts for PCA, dark current, and photocurrent at room temperature.

| Sample No. | Dark current, nA | Photocurrent, μA |
|------------|------------------|------------------|
|            | U = -50 V       | U = +50 V        | U = -50 V       | U = +50 V       |
| 1          | -30             | 16               | -0.8            | 1.1             |
| 2          | -50             | 38               | -3.1            | 2.5             |
| 3          | -40             | 25               | -1              | 1.3             |
| 4          | -45             | 40               | -1.7            | 2               |

As can be seen from Table 1, firing the contacts led to an increase in the photocurrent, on average, 2 times. The scatter in the values of the dark and photocurrent for samples (2 - 4) prepared under the same conditions is possibly due to defects in lithography, which manifests itself in a change in the distance between the electrodes. Embedding optimizes the distribution of the electric field within the structure of the photoconductive antenna. The main reason for the increase in the dark current and photocurrent in our structures after annealing is an increase in the electric field in the interelectrode gap due to the deepening of the contacts. This is explained as follows. In conventional photoconductive devices, the highest bias voltage that can be applied will be determined by the breakdown electric field of air, which is $2 \times 10^6$ V/m. In the proposed device, the greatest electric field is in the GaAs substrate, which has a higher electric breakdown field - $4 \times 10^7$ V/m. Therefore, with the same electrode gap width, the proposed device will withstand a higher bias voltage than conventional ones. This will lead to an even higher THz radiation power for the proposed device since it is obvious that the radiated THz power will increase with the applied bias.

3.2. Simulation

The PCA finite element simulation of an antenna with fired nanoscale contacts and conventional LT-GaAs protruding above the working surface has been carried out. In the finite element method used, the Maxwell wave equation with the Poisson drift-diffusion equations are jointly solved, which makes it possible to use it to calculate the current-voltage characteristics in an LT-GaAs semiconductor with given values of the mobility of charge carriers, their lifetime, depending on the power laser radiation, parameters of a Gaussian beam. The electrophysical and optical parameters of modeling were used, which are shown in Table 2.

Table 2. Conditions for growth, annealing, and annealing of contacts for PCA, dark current, and photocurrent at room temperature.

| Parameters                        | Values  |
|-----------------------------------|---------|
| LT-GaAs thickness                 | 500 nm  |
| LT-GaAs permittivity              | 12.9    |
| LT-GaAs refractive index, real part| 3.679   |
| LT-GaAs refractive index, imaginary part | 0.063  |
LT-GaAs band gap 1.42 eV
LT-GaAs affinity 4.07 eV
LT-GaAs carrier lifetime Electron: 0.1, hole: 0.4 (ps)
LT-GaAs mobility Electron: 400, hole: 100 (cm² V⁻¹ s⁻¹)
N-type doping 10¹⁵ cm⁻³
LT-GaAs Auger recombination factor 7e⁻³⁰[cm⁶/s]
Temperature 300 K
DC bias voltage 0-50 V

In figure 4 shows the electric field through the gap of the photoconductive antenna at the electrode surface (Figure 2a) and at a depth of 80 nm (Figure 2b), where the electric field in the proposed model is the highest.

Figure 4. PCA electric field profile at a depth of 80 nm, with an electrode thickness of 80 nm.

It is assumed that the highest power of the THz response of the PCA of an antenna with nanosized electrodes can be expected in the case of a higher concentration of the electric field near the edge of the electrodes due to plasmon effects. This results in higher absorption of laser radiation when the antenna surface is irradiated.

In PCA with fusion contacts, the peak of the electric field strength near the electrodes is 5.5 * 10⁷ a.u., which is slightly less than 5.8 * 10⁷ a.u. in comparison with conventional electrodes (Fig. 4), this is because there was a redistribution of the electric field in comparison with FPA without fired contacts - most of the laser radiation was absorbed in LT-GaAs. This can be seen in Fig. 5, which shows the distribution of the electric field in-depth, along the y-axis, along the direction to the antenna substrate.
Figure 5. The electric field of the simulated PCA with embedded contacts (red line) and conventional PCA (blue line) at a bias voltage of 4 V. The obtained dependences were interpolated by a linear function.

The electric field calculated at the center of the antenna gap of both conventional and proposed photoconductive antennas is plotted against the depth of the substrate, starting from the surface of the substrate, as shown in Fig. 1. The electric field strength is 1.5 times greater for PCA with fired contacts, 80 nm thick than for conventional PCA.

Analysis of experimental data and simulation results shows that firing contacts increase the photocurrent of THz PCA, as seen from Fig. 6. In Fig. 6 b) shows the simulation results, the dependence of the photocurrent on the bias voltage for PCA with fired contacts with a thickness of 80, 100, 200, 500 nm (IU80, IU100, IU200, IU500, respectively) and comparison with conventional PCA without fired contacts.

Figure 6. Dependence of the photocurrent on the bias voltage under optical laser irradiation with a wavelength of 800 nm, a) experimental data, the difference between conventional and embedded contacts; b) simulation results, a comparison was made of a conventional antenna with a contact thickness of 80 nm with a PCA with embedded contacts with different contact thicknesses: 80, 100, 200, 500 nm.

The difference between the experimental and theoretical values is because the photocurrent obtained experimentally was measured under irradiation with white light with an intensity much lower than that of a pump laser. The design of the electrodes with fired contacts makes it possible to assume that the expected THz power of the proposed one will also increase.
4. Conclusions
In this work, we simulate the PCA with a metal electrode height from 80 nm to 500 nm. The experiments carried out with the created PCA with embedded contacts demonstrated a twofold increase in the photocurrent as compared with conventional electrodes. Numerical simulation using the finite element method shows that the proposed structure of a THz antenna with fired electrodes leads to an increase in the photocurrent.

Simulation of the volt-ampere characteristics of the PCA under the influence of laser irradiation at a voltage bias of 50 V for an antenna with embedded contacts with a contact thickness of 80, 100, 200, 500 nm, in relation to a conventional PCA, showed an increase in the photocurrent generated by the antenna by 10, 12, 50 and 100%, respectively. Embedded contacts increase the electric field inside the low-temperature gallium arsenide.

5. Acknowledgments
This work was supported by the Competitiveness Program of National Research Nuclear University “MEPhI”. Samples have been fabricated and partially investigated in Shared Research Center “Heterostructure microwave electronics and Physics of wideband semiconductors”. This work was supported by Ministry of Science and Higher Education of the Russian Federation (project No. 0336-2019-0008).

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