We are IntechOpen, the world's leading publisher of Open Access books Built by scientists, for scientists

6,300

Open access books available

172,000

International authors and editors

190M

Downloads

Our authors are among the

154

Countries delivered to

TOP 1%

most cited scientists

12.2%

Contributors from top 500 universities

WEB OF SCIENCE™

Selection of our books indexed in the Book Citation Index
in Web of Science™ Core Collection (BKCI)

Interested in publishing with us?
Contact book.department@intechopen.com

Numbers displayed above are based on latest data collected.
For more information visit www.intechopen.com

Interdigitated Photoconductive Antenna for Efficient Terahertz Generation and Detection

*Shyamal Mondal, Nisha Flora Bobby Edwin
and Vaishale Rathinasamy*

Abstract

THz signals can be generated commonly from Photoconductive Antenna (PCA) but the efficiency is low for the conventional PCA. This work improves the optical to terahertz conversion efficiency of the terahertz radiation by changing the conventional PCA structure to Interdigitated PCA (IPCA). The efficiency of PCA is dependent on the current pulse generated in the antenna structure when the laser pulse is incident on it. This paper targets to achieve high photo-current, as well as THz electric field from the IPCAs which are simulated using FEM and FDTD techniques. Also, the effect of various parameters such as current, gain, frequency bandwidth, optical to terahertz conversion efficiency, etc. are studied to study the importance of IPCAs.

Keywords: interdigitated PCA, light-matter interaction, millimeter wave, photoconductive antenna, terahertz

1. Introduction

The current research and development of terahertz (THz) and millimeter wave technology at a global scale demonstrate numerous applications in medical imaging, security, high-speed communication, material characterization and spectroscopy [1]. Such applications increase the demands for efficient THz sources and detectors. Broad spectra are useful for many applications, such as time-domain spectroscopy, multi-input multi-output (MIMO) communication, etc. Photoconductive antennas (PCA) have been widely accepted as a reliable source and detector for THz generation and detection. It provides advantages for optically producing and detecting THz radiation [2]. However, there is the issue of low optical-to-THz conversion efficiency [3, 4]. Efforts have been made to enhance the efficiency by improving the laser pulse coupling, including the use of anti-reflection coating on Low-Temperature-grown Gallium Arsenide (LT-GaAs) [5], AlAs-AlGaAs based Bragg reflector under the LT-GaAs layer [6], nanoplasmonic structures [7], nanoplasmonic double layer structure [8, 9], recessed electrode and recessed nanoplasmonic array, nano-spaced electrodes [10], optical plasmonic nano-antenna [11], plasmonic nanostructure [12], graphene [13].

The design of an efficient photoconductive antenna requires a thin film of a highly resistive direct semiconductor material (III–V group) placed over the

substrate and a pair of electrodes. Low Temperature grown-Gallium Arsenide based thin film and Semi Insulating—Gallium Arsenide based substrate are normally used. The THz output power (or electric field), spectral bandwidth and optical-to-THz conversion efficiency of a PCA highly depend on its geometry, dimensions and input laser parameters [14]. Based on the aperture gap between the anode and cathode, PCAs can be classified into small gap, semi-large gap and large gap types. To improve the performance, different PCA geometries and arrays have been reported [15]. In the literature, a bow-tie PCA structure provides frequency-independent characteristics, bandwidth and power, which are widely used for THz generation [16, 17]. Experimental analysis of THz far-field radiation for a butterfly-shaped PCA was conducted by the researchers in [18]. Recent publications [19] enhance THz radiation with the ZnO nanorods, which acts as a concentrator and an anti-reflector. The increased photocurrent comes the increased local fields and the decreased backward reflection of the optical pump.

This chapter explores the prospects of an inter-digitated PCA (IPCA) for THz generation and detection. Compared to the conventional large gap dipole PCA or bow-tie PCA, the IPCA geometry shows better performance in generating THz pulses because it takes the advantages from both the small gap and large gap PCA. As the gap between the PCA electrodes is filled by the metal teeth-like structures, most of the generated photocarriers get collected at the respective electrodes with less carrier drift time and leads to the uniform electric field. The addition of slots, the number of teeth-like electrodes and teeth width dimension have been varied to study the further improvement on IPCA based THz pulse generation [20]. The IPCA with slots helps to shift the resonant frequency toward higher THz frequencies. The slots have been placed at different positions and optimized to study geometry-dependent THz signals. The slotted IPCA and IPCA modeling, simulation, experimental results and its applications have been discussed in the following sections.

2. THz generation and detection using PCA

Some of the electronic sources to generate terahertz radiation are vacuum and solid-state devices, such as the gyrotron, backward wave-oscillators, traveling wave tubes [21]. These devices are bulky and require high magnetic field. The nonlinear optical properties are exhibited for THz wave generation by nonlinear crystals like ZnTe, GaP, InGaAs via difference frequency generation (DFG) and optical rectification (OR) methods [1]. In these optical radiated THz sources, the thickness of the nonlinear material should be carefully chosen and high THz power can be generated by the high optical input power. The limitations are phase matching between the optical field and THz. Based on the optical excitation type, the THz antennas are classified into THz PCA in the pulsed system and THz photomixers in continuous wave systems. The continuous wave systems use two different frequency monochromatic lasers. The THz radiated power can be improved by enhancing the photocurrent inside the semiconducting material and also by modifying the structure of PCA. Another approach to generate the continuous THz signals is photo mixing or optical heterodyne conversion which is achieved by mixing two monochromatic continuous-wave lasers [22]. These two lasers with frequencies ω_1 and ω_2 and phases of β_1 and β_2 respectively produce beating and modulate the photoconductive switch conductance at the THz difference frequency. The combined beam is targeted on the electrodes and generate terahertz radiation with ω_0 frequency. Similar to the THz PCA, the photomixers also consists of photoconductive material, metal electrode [23]. The laser diode is used as the input optical source for the photomixers and this has advantages like compact in structure, less complexity and lightweight.

To generate THz pulsed signals, the photoconductive antenna can be used both as an emitter and detector based on ultrafast optical techniques. The photoconductive antenna shows better performance in all aspects of terahertz generation based on the photoconduction principle [24]. In terahertz pulsed systems, the DC bias voltage is applied and the photocarriers in the semiconductor photoconductive material give rise to current density and ultrafast THz pulses [25]. The photoconductive antenna is referred to as Auston switches similar to the Hertzian dipole structure discovered in 1984 by Auston [26]. This PCA is structurally similar to the RF/MW antennas. The differences are the semiconductive materials. Silicon, InGaAs, GaAs and low-Temperature grown-GaAs (LT-GaAs) are used as the substrates instead of the dielectric substrate materials [27, 28]. The PCA consists of the metal electrodes on the photoconductive material substrate with an optical laser source and bias voltage. The metal electrodes made of silver, gold, aluminum, etc., can also be used as biasing pads. This works with the photoconduction principle. The terahertz PCA can be classified into small gap antenna, semi-large gap antenna and large gap antenna based on the antenna gap size.

The performance of PCA gets affected by the geometry of the antenna, optical source, impedance matching. Some antenna structures like bow-tie PCA, dipole PCA, logarithmic spiral antenna, nanoplasmonic PCA [29], nanoantennas with plasmonic contact electrode gratings, Amplifier-driven large-area PCA, Schottky PCA, Four contact PCA, split ring resonators [30] etc., can be used as the terahertz sources and detectors. To enhance the performance of photoconductive antenna in THz radiation, the antenna structures can be optimized. The sharp edges of the electrodes are very important to produce high electric-field but its fabrication is difficult and also there is some restriction phenomenon reducing the THz photocurrent generation which are velocity overshoot phenomenon, screening effects, etc., [25, 31]. Among these designs, the interdigitated PCA shows better performance in terahertz generation and detection. Hence, the slotted IPCA and IPCA designs has been explored in next section.

3. Interdigitated PCAs

In the terahertz research area, the THz waves with high SNR and large spectral bandwidth can be emitted by using innovative antenna geometry designs. Even though the conventional PCAs have many advantages over THz generation, there are the following drawbacks as well, (i) a few photocarriers can reach the corresponding electrodes due to large antenna gap area which leads to the screening effect [32], (ii) more photo-carriers can destabilize the THz output due to thermal effect, (iii) THz output power saturates quickly with the increase of laser power, and (iv) less THz output power, hence, low optical-to-THz conversion efficiency. To overcome these disadvantages, the interdigitated photoconductive antenna (IPCA) geometry can be used. The interdigitated photoconductive antenna emits the pulsed THz wave and the interdigitated photomixers can be used to generate continuous THz waves. This structure combines both the advantages of a large and small gap antenna. The finger-like electrodes are included in the antenna gap area which helps in reducing the active area and reduces the carrier drift time. This antenna structure requires less input power to perform high E-fields and high SNR compared to other PCA designs. The THz output beam always exits the surface of the substrate in a cone and diverges very fast from the propagation direction. Usually, metal parabolic mirrors and high-index THz lenses are used with the IPCA. They help to collimate and re-focus the THz beam. The other techniques such as second metallization [33], micro-lens array [34], binary phase masking [35] are also used in integrated THz devices to have highly directional output beam.

By varying the number of metal electrodes in the IPCA gap and keeping the active area and antenna gap area constant in **Figure 1a**, the optical to terahertz conversion efficiency has been improved [21] compared to the conventional PCA. The optical to terahertz conversion efficiency of conventional PCA (dipole PCA) is very low (0.00075%) [36]. With interdigitated structures reported in [20, 37–39], the optical to terahertz conversion efficiency has been improved from 0.000614 to 0.0678% by increasing the number of interdigitated teeth from 2 elements to 40 elements. These interdigitated PCA structures can also be included in the bow-tie and dipole PCA gap area. **Figure 1** shows the schematic diagram of the interdigitated PCA, IPCA in bow-tie PCA and tip-to-tip PCA. All these PCAs have a LTg-GaAs layer of a 300 μm length, a 300 μm width and a 30 μm thickness. The metallic structures are made of silver with a 1 μm thickness. The Length of the teeth-like electrodes are also kept constant as $L_e = 21 \mu\text{m}$. The gap between the teeth-like electrodes are kept constant for all the design as $S_g = 1 \mu\text{m}$. The interdigitated PCA shown in **Figure 1a** has been designed for teeth width of 21.5 μm (i.e. 2-elements), 8 μm (i.e. 5-elements), 2.46 μm (i.e. 13-elements) and 100 nm (i.e. 40-elements). **Figure 1b** shows the IPCA is included in the conventional bow-tie PCA. Another type of IPCA is the tip-to-tip PCA (**Figure 1c**). The antenna design consists of cathode and anode electrode fingers like comb structures [40, 41]. The electric field distribution becomes strong in the middle part of the photoconductive antenna. The tip-to-tip PCA fingers are rectangular or trapezoidal shape. The trapezoidal fingers produce a stronger electric field magnitude than that of the rectangular ones [25]. Using these tip-to-tip electrodes, the large capacitance can be mitigated by

Figure 1. Schematic representation of (a) interdigitated PCA (b) IPCA in bow-tie PCA and (c) tip-to-tip PCA. The parameters L is the length of the electrode-pad, L_e is the electrode teeth length, W is the width of the electrode-pad, W_e is the width of the electrode teeth, S_g is the gap between the electrodes, S_l is the slot length and S_w is the slot width.

extending the active area of fingers. Compared with the conventional PCA, this IPCA design produces enhanced THz E-field and short carrier drift time between the electrodes. In pulsed system, the high THz radiated power can be obtained by using this efficient geometry [40–42].

4. Slotted IPCA

The slotted IPCA is another kind of interdigitated PCA. The ultrashort femtosecond laser pulse is illuminated at the centre part of the antenna. The IPCA consists of a highly defect photoconductive material LT-GaAs as substrate of a length $L_s = 300 \mu\text{m}$, a width $W_s = 300 \mu\text{m}$ and a $3 \mu\text{m}$ as thickness t . The planar silver electrode of a $1 \mu\text{m}$ thickness is placed on the substrate. The periodic metallic structures are placed at the edges of the anode and cathode with a gap of $1 \mu\text{m}$, teeth width of $W_e = 8 \mu\text{m}$ and a teeth length of $L_e = 20 \mu\text{m}$. These slots in the electrodes improve the field intensity and spectrum bandwidth for strong THz radiation [37]. By varying the geometry of interdigitated finger and slots, the performance of IPCA gets improved. **Figure 2a** shows the IPCA with two parallel slots $S_l = 40 \mu\text{m}$ and $S_w = 2 \mu\text{m}$. **Figure 2b** and **c** show the IPCA with a center slot and two side slots, where $L_w = 20 \mu\text{m}$, $S_l = 20 \mu\text{m}$ and $S_w = 2 \mu\text{m}$. The length and width of the teeth-like electrodes and substrate are consistent to those in **Figure 1**. The additional slots in the IPCA improves the performance of THz radiation. The center-slot realizes the maximum peak intensity of about 38.59 W cm^{-2} . If two parallel slots are added, the peak intensity is reduced to 27.20 W cm^{-2} . If the slots are added around the center, the peak intensity reduces to 26.44 W cm^{-2} [20]. This geometry generates high THz radiated power by optimizing the length and width of

Figure 2. Top view of slotted IPCA with (a) two parallel side slots (b) one slot at the centre and (c) two side slots about the centre. The parameters S_l is the length of the slot and S_w is the width of the slot; the color yellow signifies the electrode/metal area and the orange color indicates the substrate area.

the slot. The slot affects the current path length and the electrical length of the antenna which accounts for bandwidth enhancement, frequency shifting, and PCA compactness. These interdigitated structures with slots enhance THz field strength and reduce drift time, which are compared with conventional bare-gap antenna geometries. The electric field confinement is achieved in the active area between the interdigitated electrodes due to the slots which increases the optical to THz efficiency [38]. By increasing the slot areas and reducing slot lengths, the bandwidth and electric field of PCAs are increased, respectively.

5. Theoretical modeling of IPCA

Many models like the drift-diffusion model, electronic transport model, energy balanced approximation model, finite difference time domain model to analyze the PCA performance. Based on the drift-diffusion model, the carrier density is proportional to the optical generation rate and inversely proportional to the carrier lifetime [43]. Because of the larger mass and less mobility compared with the electrons, the contribution of holes is not considered. By using the continuity equation, the time dependent carrier density can be calculated from Eq. (1):

$$\frac{dn(t)}{dt} = -\frac{n(t)}{\tau_c} + g(t) \quad (1)$$

where, $n(t)$ is the carrier density, τ_c is the carrier lifetime and $g(t)$ is the photocarrier generation-rate. The input optical source is considered as a gaussian laser beam. The carrier-generation rate by the laser in a PCA is given in the Eq. (2).

$$g(t) = \frac{2\eta P(t)}{\pi\omega_0^2 h\nu_{\text{opt}} V} \quad (2)$$

where, η is the quantum efficiency, $P(t)$ is the optical power, ω_0 is the beam waist radius, h is Planck's constant ν_{opt} is the laser frequency, V is the active volume. The quantum efficiency η can be defined as in Eq. (3),

$$\eta = (1 - R_{\text{coeff}})[1 - \exp(-\alpha T_{LT-\text{GaAs}})] \quad (3)$$

where, R_{coeff} is the power reflection coefficient, α is the optical absorption coefficient, $T_{LT-\text{GaAs}}$ is the skin depth. With the laser beam pulse duration (τ_l) and beam waist radius ($\omega_0\omega_0$), the optical power is described as Eq. (4).

$$P(t) = P_0 \left[1 - \exp\left(\frac{-2r^2}{\omega_0^2}\right) \right] \exp\left(\frac{-2t^2}{\tau_l^2}\right) \quad (4)$$

where, P_0 is the optical peak power. The average carrier density $n_{\text{avg}}(t)$ can be calculated using the Eq. (5),

$$n_{\text{avg}}(t) = \frac{A \cdot n(t)}{V_a} \quad (5)$$

In dipole PCA, the total area of the generated carriers is given as $A = L_a \cdot W$ and the active volume is given as $V_a = L_a \cdot W \cdot T_{LT-\text{GaAs}}$, where L_a and W are the length and width of the active area respectively. While adding interdigitated fingers in the active area at the bare gap of dipole PCA, the carriers are generated in the antenna

gap between the fingers. The area of the interdigitated gap should be considered in the calculation of the IPCA structure. To know about the conduction of current across the antenna gap, the conductance can be evaluated using Eq. (6) [36],

$$G(t) = q\mu_e n(t) \left(\frac{W}{L_a} \right) T_{LT-GaAs} \quad (6)$$

where, $n(t)$ is the carrier density, μ_e is the mobility of electrons, q is the charge of an electron. A restriction phenomenon of screening effect reduces THz photocurrent due to the charge polarization [44]. The $V_c(t)$ can be calculated using the radiated voltage and the screening voltage and it is written as Eq. (7).

$$V_c(t) = V_{bias} - V_r(t) - V_s(t) \quad (7)$$

where, $V_c(t)$ is the gap capacitance voltage, $V_{bias}(t)$ is the applied bias voltage, $V_r(t)$ is the radiating voltage, $V_s(t)$ is the screening voltage. The screening voltage can be calculated in Eq. (8) [2, 36],

$$V_s(t) = V_{bias} - V_c(t) - V_r(t) \quad (8)$$

The radiated voltage can be calculated by Eq. (9),

$$V_r(t) = I_{total}(t)Z_a \quad (9)$$

where, Z_a is the antenna impedance, $I_{total}(t)$ is the total current. The capacitor current is given in Eq. (10),

$$I_c(t) = \frac{\pi q \mu_e^2 \Delta t A n(t) V_c^2(t)}{4S_g} \quad (10)$$

where, Δt is the time step. The total current flowing through the circuit is calculated using the Eq. (11),

$$I_{total}(t) = G(t)V_c(t) + I_c(t) + \frac{V_{bias}}{R_d} \quad (11)$$

where, R_d is the dark resistance. The THz photocurrent generated by the laser illumination on the semiconductor material is calculated numerically by solving the Eq. (11). The radiated THz field E_{THz} of the IPCA is directly proportional to the derivative of the terahertz photocurrent and it is calculated by Eq. (12).

$$E_{THz}(t) = \frac{I_{total}(t)}{V_a \cdot G(t)} \quad (12)$$

The THz radiated power can be calculated in Eq. (13).

$$P_{THz}(t) = I_{total}(t)^2 Z_a \quad (13)$$

There are three types of efficiencies for a PCA, such as optical to electrical conversion efficiency η_e , THz radiation efficiency η_r and matching efficiency η_m . The overall efficiency is expressed in Eq. (14).

$$\eta_t = \frac{P_{THz}(\text{peak})}{P_{opt}(\text{peak})} \quad (14)$$

P_{opt} is the optical input power and $P_{\text{THz}}(\text{peak})$ is the peak terahertz radiated power. This total efficiency can be increased by increasing the η_e , as it is the ratio of electrical power to optical power.

6. Numerical modeling of IPCA

The equivalent circuit of a dipole PCA has been simulated using the PSPICE software to obtain the photocurrent. This THz photocurrent from the equivalent circuit is also compared with the fourth order of Runge-Kutta solution in MATLAB which is shown in **Figure 3a**. The photocurrent is then input to the electromagnetic model simulation of CST Microwave studio software to obtain THz wave intensity. **Figure 3b** compares THz signals based on the equivalent circuit method and Runge-Kutta method. The THz emission intensity is observed from the continuous bias, pulsed bias and spectral bandwidth.

Compared with the conventional bare-gap geometry of PCA, the interdigitated electrodes are used to increase the optical-THz conversion efficiency. The slotted IPCA and IPCA structures have been designed and simulated using the finite difference time domain simulations of CST-Microwave Studio software. The interdigitated PCA with a slot at the centre as shown in **Figure 2b** and the IPCA without slot shown in **Figure 1a** are almost overlapped to each other. The radiation from the two slots about the centre IPCA design (**Figure 2c**) has destructive interference without enhancement effect. The same interference is found from the parallel side slot IPCA design (**Figure 2a**). Compared to the other slotted IPCA designs, the centre slot IPCA structure (**Figure 2b**) provides wide bandwidth up to 1 THz. THz E-field and gain for the slotted IPCA are shown in **Figure 4a** and **b** respectively. The IPCA without slot shows a bandwidth of 0.765 THz and its gain is about 0.223 dB and 2.389 dB respectively at 4 and 5 THz. The two side slots of IPCA design increases the center frequency to 2.695 THz and results pulse width of 0.7035 ps. The two slots around the center performs the spectrum bandwidth of 1.29 THz and the 0.782 and 3.232 dB gain respectively. The center slot IPCA performs a 0.515 THz bandwidth and 0.613 and 3.013 dB gain respectively at 4 and 5 THz. It performs high-intensity THz wave generation [37]. The tip-to-tip IPCA shown in **Figure 1c** has the electric-field of about 4.5×10^6 V/m. The bow-tie antenna coupled with IPCA (**Figure 1b**) can enhance the THz generation.

The time-dependent average carrier density of IPCA is plotted via Eq. (5) and MATLAB software in **Figure 5a**. The carriers are largely generated in a large active area gap based on Eq. (1). The carrier density is high in a dipole PCA, comparing to the designed IPCA as it has a large gap between the anode and cathode. The n_{avg} of a

Figure 3.

(a) Normalized THz photocurrent (b) intensity of THz signal (reprinted from [45] with permission of Springer publishing).

Figure 4.
 (a) Simulated E-field for the slotted IPCA and (b) gain for the slotted IPCA (reprinted from [21], with permission of IEEE publishing).

Figure 5.
 Simulated results of (a) Total current of dipole and IPCA (b) radiated power of dipole and IPCA and (c) optical-THz conversion efficiency of dipole and IPCA.

dipole PCA is about $4.89 \times 10^{23} \text{ m}^{-3}$. For the 100 nm IPCA is $1.02 \times 10^{23} \text{ m}^{-3}$. Due to a larger gap, the screening effect become obvious to reduce THz intensity generation. **Figure 5b** shows the current conduction across the IPCA gap based on Eq. (6). The interdigitated gap conductance $G(t)$ depends on the carrier mobility, laser input power, carrier lifetime, antenna geometry and laser pulse duration. When the number of metal teeth structures increases in an active area, the conductance increases with the electric field amplitude based on Eq. (12). The IPCA teeth width of 100 nm possess conductance of 0.15048 Ω whereas the conventional dipole PCA possess 0.000173 Ω with 250 mW input optical power. To calculate THz radiation power of an IPCA, the antenna radiation resistance is required based on Eq. (13). Hence, the IPCA can be designed using the Finite Element Method (FEM) within Ansys High-Frequency Structure Simulator (HFSS) package. Among the real and imaginary part resistance of an antenna, only the real part resistance is dependent on THz frequency. All the IPCA designs radiates maximum power at 0.4 THz and hence the real part ohmic resistance is considered at that particular frequency which is shown in **Figure 5c**.

Figure 6. (a) Simulated E-field for the IPCA and (b) gain for the different elements of IPCA (Reprinted from [21], with permission of IEEE publishing).

The IPCA total current, THz radiation power and Opt-THz conversion efficiency of dipole PCA and IPCA structures are plotted in the **Figure 6** based on Eqs. (1)–(14). The antenna gap widths are $1\mu\text{m}$ for all IPCA designs. The amplitude of current gets increased by high carrier generation. In PCA, the antenna radiates toward the substrate. THz radiation power and efficiency are plotted based on Eqs. (13) and (14) respectively. Increasing the input pump power leads to high radiation power. Even with low input power of 250 mW, the IPCA of width 100 nm (40-elements) radiates up to 2.962 mW. The total current for the 40-elements IPCA is about 0.939 A whereas 0.12 A for the dipole PCA. The total efficiency for the dipole PCA is about 0.001% and that of the 40-elements IPCA is about 0.06%. Comparing to the dipole PCA, an IPCA efficiency as high as 60 orders of magnitude.

By increasing the interdigitated elements in the active area of an IPCA, the enhanced electric field is obtained, which is shown in **Figure 7a**. **Figure 7b** depicts the corresponding spectra which clearly show the gain fluctuation for 2, 5 and 13 interdigitated elements. The 2, 5 and 13-elements possess peak intensities of 24.86, 26.42 and 27.66 W/cm^2 respectively. Hence, designing the antenna with the various numbers of interdigitated elements can control THz radiation spectra.

Figure 7. Simulated results (a) average carrier density of dipole and IPCA (b) gap conductance of dipole and IPCA and (c) antenna resistance of dipole and IPCA.

7. Experimental results of IPCA

The experimental results of IPCA antennas are presented in this section. The micrograph of an IPCA device and its cross sectional view are given in **Figure 8a** and **b** respectively. The fabrication process of this device involves the following steps. First of all, the electrodes are deposited on top of a lattice-matched layer system consisting of 150 nm SI-GaAs, a 100 nm AlAs layer, followed by a 1.3 μm layer of LT-GaAs. The LT-GaAs is grown using molecular beam epitaxy on a SI-GaAs substrate. The photolithography technique has been used to pattern the electrode using mask and photoresist. The metal along with AlAs layer has been etched out in a HF solution resulting the gap in interdigitated electrode structure, shown in **Figure 8b**. The IPCA array chip is then transferred to an optically and terahertz transparent sapphire substrate of 500 μm thickness.

To measure the THz radiation from IPCA single element and IPCA array, the device is placed in a standard confocal terahertz-time-domain spectroscopy system (THz-TDS) and pumped by the optical beam from an ultrafast Ti:sapphire laser, operating at 780 nm having a repetition rate of 76 MHz with a pulse width of 100 fs. The IPCA has been placed normally to the femtosecond laser beam and the terahertz radiation exits the substrate (sapphire) side along with the residual pump beam. For the generation of THz signal from the IPCA, the substrate lens is not used. However, a silicon substrate lens is used for THz detection. The typical bias voltage of 0–40 V amplitude square wave is used for biasing. For the detection system, the same IPCA is used with 3 mm diameter silicon substrate lens to focus the terahertz radiation onto the photoconductive gap. The normalized electric field for the IPCA is obtained from THz-TDS and the corresponding frequency spectra are depicted in **Figure 9**. The figure shows around 30% increase in THz amplitude between the single and array IPCA. In order to identify the reason for increasing THz radiation, the optical excitation area is measured (**Figure 9**). Due to higher amount of radiation, a strongly directed THz beam (**Figure 10**) produces a large

Figure 8.
(a) Micrograph of terahertz IPCA device. (b) Cross-sectional view of terahertz IPCA array (reprinted from [46] with permission of Applied Physics Letters publishing).

Figure 9. Time-resolved scans of terahertz pulse for IPCA array emitter (dark line) and single element IPCA (light line) and their respective spectra in inlay (reprinted from [46] with permission of Applied Physics Letters publishing).

Figure 10. (Color online) Calculated radiation pattern for dipole (black solid) line and measured single element IPCA radiation pattern (dashed line). IPCA array radiation pattern calculated based on array theory (light solid line) and measurement (dotted). Inlay: experimental setup with fiber coupled and dispersion compensated (FC) receiver for radiation pattern measurement (reprinted from [46] with permission of Applied Physics Letters publishing).

THz wave amplitude at the detector which is collected using the parabolic mirrors in the measurement setup.

8. Conclusion

The enormous demand for future wireless applications of THz waves motivates the researchers to target on the development of THz sources and detectors. Among all the conventional PCAs, IPCAs improve THz generation and detection. The analytical calculations of IPCA helps us to understand capacitive behavior of the gap between the electrodes. From the above discussed results, it has been observed that the photocurrent and optical to THz conversion efficiency are enhanced by the IPCA design compared with the dipole PCA. THz performance can be further improved by introducing the non-linear effect in the IPCA active area or by the plasmonic features.

IntechOpen

Author details

Shyamal Mondal^{1*}, Nisha Flora Bobby Edwin² and Vaishale Rathinasamy²

¹ Department of Applied Physics, Defense Institute of Advanced Technology, Pune, India

² Department of Electronics and Communication Engineering, SRM Institute of Science and Technology, Chennai, India

*Address all correspondence to: shyamal.kgec@gmail.com

IntechOpen

© 2022 The Author(s). Licensee IntechOpen. This chapter is distributed under the terms of the Creative Commons Attribution License (<http://creativecommons.org/licenses/by/3.0>), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

References

- [1] Tonouchi M. Cutting-edge terahertz technology. *Nature Photonics*. 2007; **1**(2):97-105
- [2] Khiabani N, Huang Y, Shen YC, Boyes S. Theoretical modeling of a photoconductive antenna in a terahertz pulsed system. *IEEE Transactions on Antennas and Propagation*. 2013;**61**(4): 1538-1546
- [3] Yardimci NT, Yang SH, Jarrahi M. High power pulsed terahertz radiation from large area plasmonic photoconductive emitters. In: 2015 40th International Conference on Infrared, Millimeter, and Terahertz waves (IRMMW-THz). Conference and proceedings: IEEE; 2015. pp. 1-2
- [4] Collier CM, Stirling TJ, Hristovski IR, Krupa JD, Holzman JF. Photoconductive terahertz generation from textured semiconductor materials. *Scientific Reports*. 2016;**6**(1):1-10
- [5] Headley C, Fu L, Parkinson P, Xu X, Lloyd-Hughes J, Jagadish C, et al. Improved performance of GaAs-based terahertz emitters via surface passivation and silicon nitride encapsulation. *IEEE Journal of Selected Topics in Quantum Electronics*. 2010;**17**(1):17-21
- [6] Mitrofanov O, Brener I, Luk TS, Reno JL. Photoconductive terahertz near-field detector with a hybrid nanoantenna array cavity. *ACS Photonics*. 2015;**2**(12):1763-1768
- [7] Yang SH, Hashemi MR, Berry CW, Jarrahi M. 7.5% optical-to-terahertz conversion efficiency offered by photoconductive emitters with three-dimensional plasmonic contact electrodes. *IEEE Transactions on Terahertz Science and Technology*. 2014;**4**(5):575-581
- [8] Bashirpour M, Kolahdouz M, Neshat M. Enhancement of optical absorption in LT-GaAs by double layer nanoplasmonic array in photoconductive antenna. *Vacuum*. 2017;**146**:430-436
- [9] Ghorbani S, Bashirpour M, Poursafar J, Kolahdouz M, Neshat M, Valinejad A. Thin film tandem nanoplasmonic photoconductive antenna for high performance terahertz detection. *Superlattices and Microstructures*. 2018;**120**:598-604
- [10] Bashirpour M, Ghorbani S, Forouzmehr M, Kolahdouz M, Neshat M. Optical absorption enhancement in LTG-GaAs for efficiency improvement of THz photoconductive antennas. In: 2016 Fourth International Conference on Millimeter-Wave and Terahertz Technologies (MMWaTT). Conference and proceedings: IEEE; 2016. pp. 14-16
- [11] Lepeshov S, Gorodetsky A, Krasnok A, Toropov N, Vartanyan TA, Belov P, et al. Boosting terahertz photoconductive antenna performance with optimised plasmonic nanostructures. *Scientific Reports*. 2018; **8**(1):1-7
- [12] Yardimci NT, Jarrahi M. High sensitivity terahertz detection through large-area plasmonic nano-antenna arrays. *Scientific Reports*. 2017;**7**(1):1-8
- [13] Akbar F, Kolahdouz M, Larimian S, Radfar B, Radamson H. Graphene synthesis, characterization and its applications in nanophotonics, nanoelectronics, and nanosensing. *Journal of Materials Science: Materials in Electronics*. 2015;**26**(7):4347-4379
- [14] Nguyen TK, Park I. Effects of antenna design parameters on the characteristics of a terahertz coplanar stripline dipole antenna. *Progress in Electromagnetics Research*. 2013;**28**: 129-143

- [15] Zhu N, Ziolkowski RW. Photoconductive THz antenna designs with high radiation efficiency, high directivity, and high aperture efficiency. *IEEE Transactions on Terahertz Science and Technology*. 2013;3(6):721-730
- [16] Alias NB, Awang AH. Physical parametric analysis of Terahertz Photoconductive bow-tie dipole Antenna on frequency and radiation pattern using electromagnetic simulation tools. In: 2016 IEEE Asia-Pacific Conference on Applied Electromagnetics (APACE). IEEE; 2016. pp. 263-267
- [17] Khiabani N. Modelling, Design and Characterisation of Terahertz Photoconductive Antennas. Ireland, UK: The University of Liverpool; 2013
- [18] Zhang J, Tuo M, Liang M, Ng WR, Gehm ME, Xin H. Terahertz radiation of a butterfly-shaped photoconductive antenna. *Hongwai yu Jiguang Gongcheng/Infrared and Laser Engineering*. 2019;48(4):0402001
- [19] Bashirpour M, Forouzmehr M, Hosseiniadjad SE, Kolahdouz M, Neshat M. Improvement of terahertz photoconductive antenna using optical antenna array of ZnO nanorods. *Scientific Reports*. 2019;9(1):1-8
- [20] Mondal S, Rathinasamy V, Kapoor S, Mukherjee S, Rao TR. Interdigitated photoconductive antenna design and analysis for terahertz wireless applications. In: 2020 IEEE 3rd 5G World Forum (5GWF). IEEE; 2020. pp. 484-487
- [21] Tucek J, Gallagher D, Kreischer K, Mihailovich R. A compact, high power, 0.65 THz source. In: 2008 IEEE International Vacuum Electronics Conference. Conference and proceeding: IEEE; 2008. pp. 16-17
- [22] Gregory IS, Baker C, Tribe WR, Bradley IV, Evans MJ, Linfield EH, et al. Optimization of photomixers and antennas for continuous-wave terahertz emission. *IEEE Journal of Quantum Electronics*. 2005;41(5):717-728
- [23] Duffy SM, Verghese S, McIntosh A, Jackson A, Gossard A, Matsuura S. Accurate modeling of dual dipole and slot elements used with photomixers for coherent terahertz output power. *IEEE Transactions on Microwave Theory and Techniques*. 2001;49(6):1032-1038
- [24] Ferguson B, Zhang XC. Materials for terahertz science and technology. *Nature Materials*. 2002;1(1):26-33
- [25] Cai Y, Brener I, Lopata J, Wynn J, Pfeiffer L, Federici J. Design and performance of singular electric field terahertz photoconducting antennas. *Applied Physics Letters*. 1997;71(15):2076-2078
- [26] Auston DH. Picosecond optoelectronic switching and gating in silicon. *Applied Physics Letters*. 1975; 26(3):101-103
- [27] Pozar D. Chebyshev multisection matching transformers. In: *Microwave Engineering*. 4th ed. Hoboken, NJ, USA: John Wiley & Sons, Inc; 2012. pp. 256-261
- [28] Singh D, Kalialakis C, Gardner P, Hall PS. Small H-shaped antennas for MMIC applications. *IEEE Transactions on Antennas and Propagation*. 2000; 48(7):1134-1141
- [29] Llatser I, Kremers C, Cabellos-Aparicio A, Jornet JM, Alarcón E, Chigrin DN. Graphene-based nanopatch antenna for terahertz radiation. *Photonics and Nanostructures-Fundamentals and Applications*. 2012; 10(4):353-358
- [30] Deng H, Xiong Z, Qu W, Wu Z, Liu Q, Chen L, et al. The impact of structural parameters of split-ring resonators on the terahertz radiation

characteristics of micro-structured photoconductive antennas: A simulation study. *IEEE Photonics Journal*. 2020;**12**(3): 1-13

[31] Tani M, Matsuura S, Sakai K, Nakashima SI. Emission characteristics of photoconductive antennas based on low-temperature-grown GaAs and semi-insulating GaAs. *Applied Optics*. 1997;**36**(30):7853-7859

[32] Mikulics M, Michael E, Schieder R, Stutzki J, Güsten R, Marso M, et al. Traveling-wave photomixer with recessed interdigitated contacts on low-temperature-grown GaAs. *Applied Physics Letters*. 2006;**88**(4):041118

[33] Vieweg N, Mikulics M, Scheller M, Ezdi K, Wilk R, Hübers HW, et al. Impact of the contact metallization on the performance of photoconductive THz antennas. *Optics Express*. 2008; **16**(24):19695-19705

[34] Matthäus G, Nolte S, Hohmuth R, Voitsch M, Richter W, Pradarutti B, et al. Microlens coupled interdigital photoconductive switch. *Applied Physics Letters*. 2008;**93**(9):091110

[35] Ropagnol X, Morandotti R, Ozaki T, Reid M. THz pulse shaping and improved optical-to-THz conversion efficiency using a binary phase mask. *Optics Letters*. 2011;**36**(14):2662-2664

[36] Prajapati J, Bharadwaj M, Chatterjee A, Bhattacharjee R. Circuit modeling and performance analysis of photoconductive antenna. *Optics Communications*. 2017;**394**:69-79

[37] Rathinasamy V, Kapoor S, Rout A, Rao TR, Mondal S. Interdigitated-slot photoconductive antenna for terahertz applications. In: *IEEE Indian Conference on Antennas and Propagation (InCAP)*. IEEE; 2019, 2019. pp. 1-3

[38] Rathinasamy V, Thipparaju RR, Edwin NFB, Mondal S. Interdigitated

photoconductive terahertz antenna for future wireless communications. *Microwave and Optical Technology Letters*. 2021

[39] Bobby ENF, Rathinasamy V, Rao TR, Mondal S. Parametric analysis of inter-combed photoconductive antenna for terahertz communication. In: *2021 International Conference on Communication information and Computing Technology (ICCICT)*. Conference and proceedings: IEEE; 2021. pp. 1-4

[40] Berry CW, Wang N, Hashemi MR, Unlu M, Jarrahi M. Significant performance enhancement in photoconductive terahertz optoelectronics by incorporating plasmonic contact electrodes. *Nature Communications*. 2013;**4**(1):1-10

[41] Tanoto H, Teng J, Wu Q, Sun M, Chen Z, Maier S, et al. Greatly enhanced continuous-wave terahertz emission by nano-electrodes in a photoconductive photomixer. *Nature Photonics*. 2012; **6**(2):121-126

[42] Seo M, Park H, Koo S, Park D, Kang J, Suwal O, et al. Terahertz field enhancement by a metallic nano slit operating beyond the skin-depth limit. *Nature Photonics*. 2009;**3**(3):152-156

[43] Brown E, Smith F, McIntosh K. Coherent millimeter-wave generation by heterodyne conversion in low-temperature-grown GaAs photoconductors. *Journal of Applied Physics*. 1993;**73**(3):1480-1484

[44] El-Ghazaly SM, Joshi RP, Grondin RO. Electromagnetic and transport considerations in subpicosecond photoconductive switch modeling. *IEEE Transactions on Microwave Theory and Techniques*. 1990;**38**(5):629-637

[45] Nissiyah GJ, Madhan MG. A simple equivalent circuit model of photoconductive dipole antenna for the

study of terahertz intensity modulation.
Optical and Quantum Electronics. 2021;
53(4):1-22

[46] Awad M, Nagel M, Kurz H,
Herfort J, Ploog K. Characterization of
low temperature GaAs antenna array
terahertz emitters. Applied Physics
Letters. 2007;**91**(18):181124