Enhancement of optical absorption in LT-GaAs by double layer nanoplasmonic array in photoconductive antenna

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Abstract

At the moment, weak optical absorption and small photocurrent of the terahertz photoconductive antennas (PCA) have forced scientific community to design and develop antennas with higher efficiencies. In this work, a novel configuration consists of a double layer nanodisk arrays has been proposed and thoroughly investigated. These arrays are able to couple the plasmon resonance to terahertz PCAs. The finite difference time domain (FDTD) method has been used to extract the characteristics of the proposed structure. The simulation results have indicated that the absorption of the proposed structure increase to more than 76% as compared to around 31.5% for conventional structures without any nanostructure and 46% for one layer nanoplasmonic structure in 800 nm wavelength. Optimized one layer nanoplasmonic array increases photocurrent up to 10.1 nA that indicates 1022% enhancement in comparison with conventional structure. Using the double layer nanoplasmonic array results in 144% light absorption enhancement, and 3433% photocurrent enhancement in comparison with the conventional structure.

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1. Introduction

In the last decade, the industry demands are moving much faster to the terahertz (THz) spectrum with interesting potential applications in security and medical imaging, spectroscopy and indoor communication because of its unique properties [1–5]. The most important component of THz technology is the source. Unlike infrared and microwave frequency, there is no efficient source in THz spectrum. Lack of high power sources and sensitive detectors are the main reasons for slowing down the progress of THz technology. There has been lots of efforts to apply the electronic techniques from lower band and optical techniques from upper band to terahertz wave generation devices [6–9]. Electronic techniques because of 1/f power degradation, and optical methods because of lacking photosensitive materials with desired bandgap could not play a promising role in THz wave generation technology over the last decades [10,11]. The most common method for THz wave generation and detection is through using PCAs due to their compact structure, simple fabrication, room temperature operation and broadband pulse nature [12]. PCAs are widely used in time-domain THz imaging and spectroscopy systems for generating pulsed THz radiation [4,13]. Transient photocurrent in sub picosecond time scale lifetime semiconductor is responsible for terahertz radiation in PCAs. When the device is illuminated by a femtosecond laser, photocarriers are excited in the photosensitive semiconductor and accelerated by an applied bias voltage between two electrodes. The drifted photo-carriers result in a sub-picosecond photocurrent that couples to the antennas to radiate terahertz wave [14]. The most important part of a PCA is its photosensitive semiconductor. So far, low temperature GaAs (LT-GaAs) has been the best choice for THz PCA fabrication because of its high dark resistance, very short carrier lifetime, high breakdown voltage and high power saturation [15]. In the past few years, other materials, such as graphene, InGaAs, InP, SiGe and SiC have been used as the photosensitive material [11,16–21]. However, mentioned materials do not have all advantages of LT-GaAs such as appropriate band gap for commercial 800 nm femto laser, mature fabrication technology, short lifetime, production cost and resistivity.

Low optical to THz conversion efficiency is the most challenging issue that limits the PCA applications. Part of such limitation originates from inadequate laser pulse absorption by photoconductive materials. Therefore, a light trapping scheme is needed for the design of high efficiency PCA to enhance light absorption [22]. One promising method to improve the laser pulse absorption in photoconductive materials is based on incorporating...
nanoplasmonic structures in them [22–28]. It has been proven that using nanoplasmonic structures is very effective in improving the quantum efficiency of photoconductive THz devices. The reason for this fact originates from unique capability of nanoplasmonic structures to enhance the absorption of incident laser pulses. Moreover, the resulting higher electric field near the PCA surface results in more photo-carriers in close proximity of the device surface which in turn leads to an increased transient photocurrent. As the number of photocarriers in the sub pico-second timescale increases, higher quantum efficiency will be achieved and so will output THz power. Berry et al. have achieved up to two orders of magnitude enhancement in THz PCA efficiency by use of nanoplasmonic structures in combination with the reduced photo-carrier transport distance [29].

To have a more efficient PCA fabrication process considering time and cost, implementing a computer simulation software to investigate different ideas is desired. There has been a lot of efforts to implement a reliable method to simulate and investigate the effect of different parameters on the PCA performance [30–32]. Jafarlou et al. have reported using the FDTD method to investigate the effect of plasmonic nano-grating on the terahertz photomixer performance. They showed that using nano-grating electrodes enhances the optical absorption by a factor of around 1.4 at the optical resonances by suppressing light reflection from the surface [31]. In other work, Burford et al. used a nanodisk array on top of a 120 nm LT-GaAs layer with the antenna electrodes located below the photoconductive layer. Their results demonstrated significant increase in the conversion of optical waves to photocurrents as compared with conventional antennas [33]. This challenging problem handling needs combination of Maxwell’s equations, the drift-diffusion equations and continuity relations [34,35].

In this paper, a new structure is proposed that benefits from a double layer gold nanodisk array to enhance optical absorption of the photosensitive material. According to the best of our knowledge, it is the first time that a double layer nanoplasmonic structure has been used to improve the photoconductive antenna performance. The proposed structure nanoplasmonic array’s periodicity, height and width have been investigated and optimized by use of FDTD method to improve the efficiency of structures. The introduced PCA benefits from the low reflection and high absorption simultaneously. By use of top nanoplasmonic array, more light enters the LT-GaAs layer and the bottom nanoplasmonic array traps the light inside the LT-Gas and increases the number of the photo-generated carriers. Results showed that proposed structure has increased the photocurrent remarkably.

2. Structure design and simulation method

The main reference structures (structure I) was composed of a LT-GaAs layer and two gold antennas without any nanoplasmonic structure (see the structural parameters in Fig. 1a and b). As it can be seen in Fig. 1a and b, the structure consists of a LT-GaAs substrate, SiO2 antireflection layer and two gold electrodes. The photosensitive layer was 500 nm thick LT-GaAs and the gap (g) between two electrodes was 2 μm. The SiO2 antireflection layer with 300 nm thickness was deposited on the LT-GaAs layer. Structure II

![Schematic diagram of (a) Reference Structure (Structure I). (b) Reference structure side view at y = 0 nm. (c) Simple one layer plasmonic array structure (Structure II). (d) Simple one layer plasmonic array side view at y = 0 nm. (e) Proposed structure (Structure III). (f) Proposed structure side view at y = 0 nm.](image-url)
was designed benefiting from a top surface array (Fig. 1c and d) and simulated for comparison with structure III. The schematic of the main proposed metal-semiconductor-metal (MSM) structure (structure III) are shown in Fig. 1e and f. In the proposed structure (Fig. 1e), an array of metallic nanodisk have been used on both top and bottom of LT-GaAs layer as an optical trapping scheme. FDTD method has been used to solve the Maxwell’s wave equation. The simulated structure were illuminated by an 800 nm Gaussian laser with 10 fs pulse width and the voltage applied between two electrodes was 10 V. The boundary condition was set to ensure that the absorption is because of the proposed structure photon trapping and not the reflection from the boundaries. Other FDTD parameters are illustrated in Table 1.

To calculate the photocurrent, first, electron-hole generation profile was extracted from FDTD method. Then, the extracted generation profile was applied to the drift-diffusion model in combination with the continuity equation to calculate the photocurrent. The 2 dimensional (2D) finite element method (FEM) with 40 nm maximum mesh size at \( y = 0 \) plane was used to solve drift-diffusion model equations. The parameters used in the FEM simulation are summarized in Table 2.

### Results and discussion

As a proof of sanity to check if the proposed structure can improve the THz absorption, all three designs have been simulated with a set of random primary dimensions and the results of optimized structures are demonstrated in Fig. 2. For both structures II and III, a nanoplasmonic array of top surface with nanodisks of 140 nm height, 140 nm Diameter and 500 nm periodicity were used. The bottom array consisted of nanodisks with 150 nm height, 140 nm Diameter and 500 nm periodicity. Fig. 2a illustrates the absorption efficiency results of the simulation on a conventional PCA as the reference structure. It can be seen that 31.5% of the power of the 800 nm fs laser is absorbed in LT-GaAs layer and more than 29% is reflected from the surface (Fig. 2d). The rest of illuminated power (remained 39.5%) is not absorbed by LT-GaAs layer and transmits through the PCA. So, there are two ideas to enhance the absorption efficiency of this structure; 1) Reducing the reflection

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**Table 1**

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**Table 2**

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**Fig. 2.** Absorption efficiency of (a) reference structure (Structure I), (b) One layer nanoplasmonic structure (Structure II) and (c) the proposed double layer nanoplasmonic structure (structure III) and (d) reflectance of structures I, II and III at 800 nm.
from LT-GaAs surface. 2) Trapping the laser beam in the LT-GaAs layer. More absorption efficiency means higher photocurrent which leads to higher THz wave generation. Fig. 2b shows the absorption efficiency of structure II. The absorption efficiency is enhanced by 46% at 800 nm wavelength and the reflectance decreases to less than 9% (Fig. 2d). Structure III benefits from very low reflectance (less than 9%) of structure II and at the same time, increases the absorption efficiency up to 77% (Fig. 2c). In this structure, decrease of the reflectance using the surface nanoplasmonic array occurs because of an artificial refractive index between air and LT-GaAs. This increases the local field near the surface of PCA by plasmon excitation. The bottom nanoplasmonic array has two major effects on the light behavior. First, it decreases the laser transmission through the structure by reflecting the light back to the PCA and second, it excites plasmon waves on the metal surface and increases the local field around 300 nm under the surface of LT-GaAs. These two phenomena enhance the optical absorption and electron-hole generation rate which in turn results in higher transient photocurrent.

Fig. 3a–c are illustrating the E-field distribution of structure I, II and III, respectively. For sake of better understanding and comparison, the surface E-field (at z = 500 nm) of three structures are extracted and shown in Fig. 4a. It can be clearly seen that the electric field at the metal/semiconductor interface is high and decreases significantly by moving away from the interface (see Fig. 4b–d). It is also observed that the ratio of the local field to the illuminated laser field (γ = |E/E_in|) close to the metal/LT-GaAs interface is increased from 0.4 for structure I to 8.6 for structure II and to 9 for structure III. This remarkable field enhancement factor (δ = 2.4 δ = 21.5) in structure III in comparison to structure I causes more photon generation and more photocurrent.

Comparing Fig. 4a–d, one concludes that by moving from surface to bottom of LT-GaAs layer, difference between electric field distribution of structure II and III increases. Higher electric field in structure III is the main reason of higher photocurrent in this device. Sharp points in Fig. 4d are the consequence of the plasmonic field generated by the bottom gold nanodisk array.

In order to maximize the generated photocurrent, first, geometrical parameters of structure II were investigated. Then for the second step, bottom nanodisk were added to the structure (structure III) and by keeping the optimized surface parameters, bottom nanodisk array’s periodicity, height and radius were varied to reach an optimal conversion efficiency. Our approach, step by step optimization of the layout, can even be investigated using parallel optimization of top and bottom layout but needs a very stronger computing center. Fig. 5a–c illustrates the photocurrent of structure II for different geometrical parameters. First, nanodisk height (u_H) and diameter (u_D) fixed at 90 nm and 200 nm respectively and the periodicity (u_P) scanned from 300 nm to 550 nm. The Maximum photocurrent of 3.6 nA obtained at 500 nm (Fig. 5a). In the second step, periodicity was fixed at 500 nm and nanodisk height was scanned from 50 nm to 180 nm at u_D = 200 nm. According to Fig. 5b, highest photocurrent of 4 nA obtained at u_D = 140 nm. At last, periodicity and height were fixed at 500 nm and 140 nm respectively and the diameter was varied from 100 to 300 nm. The result of simulation is shown at Fig. 5c and compared with structure I photocurrent. The maximum photocurrent of 10.1 nA was obtained at u_D = 140 nm and 1022% enhancement in comparison with structure I was observed.

In order to further optimize the structure, the bottom nanodisks were added to the design. The generated photocurrent was again investigated for different sizes (height and radius) and layouts (periodicity) of the bottom nanodisk arrays (see Fig. 6a–c) and compared with structure II. In the full-field simulation, top surface nanodisk array’s height (u_H), periodicity (u_P) and diameter (u_D) were fixed to 140 nm, 500 nm and 140 nm (the optimized result for structure II), respectively. To study the effect of the bottom nanodisk array’s diameter (b_P) on the photocurrent, the primary values for the bottom array were chosen as follows; the periodicity of was fixed to 500 nm and the height of nanodisks (b_H) was 200 nm. As shown in Fig. 6a, the diameter of the bottom array was altered from 50 to 160 nm and maximum photocurrent of 23.5 nA was obtained for nanodisks with 140 nm diameter. In the next step, the diameter was fixed at 140 nm and the height was swept, at periodicity of 500 nm, from 100 to 200 nm. According to Fig. 6b, the maximum photocurrent of 31.8 nA was obtained at height of 150 nm. The photocurrent as a function of periodicity is plotted in Fig. 6c. Increasing the periodicity from 300 to 600 nm first enhances the photocurrent because of lowering the transmission from the substrate. According to Fig. 6c, the photocurrent has a maximum
Fig. 4. Normalized surface electric field comparison among structure I, II and III at (a) $z = 500$ nm (b) $z = 350$ nm (c) $z = 200$ nm (d) $z = 100$ nm.

Fig. 5. Photocurrent of structure II for (a) nanodisk array periodicity sweeping at $u_D = 200$nm, $u_H = 90$nm, (b) nanodisk array height sweeping at $u_D = 200$nm, $u_P = 425$ (c) nanodisk array diameter sweeping at $u_H = 500$nm, $u_H = 140$nm.
around to 500 nm and then drops. Using this value leads to achieve higher THz field power which is parabolically related to the photocurrent. Maximum photocurrent of 31.8 nA was thus calculated at height of 150 nm, diameter of 140 nm and periodicity of 500 nm for the bottom array. The top surface nanodisk array height of 140 nm, diameter of 140 nm, and periodicity of 500 nm were used in the final design. It is worth to be noted that using structure III (proposed structure) results in 3433% photocurrent enhancement in comparison with the structure I (a flat structure without nanoplasmonic structure) and 214% enhancement in comparison with structure II (the one with just top layer nanoplasmonic structure).

4. Conclusion

In conclusion, a new design of THz PCA based on a double-layer nanoplasmonic array was introduced and the effects of geometrical parameters on the generated photocurrent were investigated by use of FDTD method. By sweeping the periodicity, height and radius of nanoplasmonic arrays on top, maximum photocurrent of 10.1 nA has achieved for \( u_p = 500 \text{ nm}, \ u_H = 140 \text{ nm} \) and \( u_D = 140 \text{ nm} \). According to the results, the absorption efficiency is enhanced by 46% at 800 nm wavelength and the reflectance decreased to less than 9% for one layer nanoplasmonic structure. By introducing the bottom nanoplasmonic layer and optimizing the geometrical parameters, the highest photocurrent (maximum photocurrent = 31.8 nA) has been extracted. The reflectance of the proposed double layer nanoplasmonic structure reduced to less than 9% and absorption efficiency increased up to 77%. Our step by step optimization approach can be done using a normal computing system. By 3433% enhancement of the photocurrent, the proposed structure has showed a promising path to acquire high efficiency PCAs.

References
