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# Promising Materials for Photoconductive Antenna for THz Generation

Review on Photoconductive Antenna Design from Conventional to Microstructures

**Hemant Kumar**

Motilal Nehru College (University of Delhi, South Campus), Benito Jurez Road, New Delhi – 110021, India
Email: *hkumar. du[at]gmail.com*

**Abstract:** ***Photoconductive antenna (PCA) is a widely known device for terahertz generation and detection. Since the 1980s, several variants for PCA substrate materials and antenna design have been researched and proposed for furthering the bandwidth of the device. PCA technology is therefore the cornerstone of terahertz (THz) spectroscopic and imaging system and thus its enhancement, not only in terms of field strength but commercial value is important. In this review article, we provide an overview on different materials used for fabrication of PCA devices using simple lithographic processing. We investigate the pre-requisites for enhanced THz field strength based on latest trends in material technology for THz field.***

**Keywords:** Photoconductive antenna, Terahertz, Laser pulses, Epitaxial layer, Material technology

## 1. Introduction

Semiconductors exhibit many diverse phenomena under terahertz-frequency electromagnetic radiation (THz) due to the fact that the energy of THz photons corresponds to significant energy scales in bulk and low-dimensional materials and devices. With regard to broadband THz sources, various inorganic crystals such as ZnTe/GaP/GaAs/GaSe/DAST/LiNbO3 have been used which are pumped by femtosecond laser pulses. These pulses are combined with field-resolved detection through electro-optic sampling using similar crystals [1]. Photoconductive devices have been the most successful method to generate terahertz radiation. In 1981, Mourou et al. reported the generation of picosecond microwave pulses in free space by optically switching a photoconductive gap and using the resulting electrical transient to drive an RF antenna [2]. Later, Auston and co-workers [3] altered the device by integrating the photoconductor into the antenna structure, thereby developing a device called a photo conducting dipole antenna. This structure causes a free space propagation of THz radiation, without the need tocouple the field into a transmission line.

The development of pulsed THz radiation from PCAs is linked tothe advancement of ultrafast lasers such as Ti-sapphire laser, which is capable of generating light pulses ranging from picoseconds (ps) to femtosecond (fs). PCAs are promising THz radiation sources because of the fact that their operation can occur at room temperature without cryogenic cooling. THz generation can be divided into two categories: 1) optical rectification and 2) photoconductive (PC) generation. To produce highly energetic THz pulses, optical rectification is the most appropriate procedure, whereas photoconductive emission is suitable efficient in case of standard laser oscillating systems.

The THz radiations from a PCA can be explained and comprehended by transient acceleration of charge carriers in bulk semiconducting material and collection of photo carriers by the electrodes of antenna [4, 5]. When a femto second optical pulse is incident in the gap of a THz PCA, electron–hole pairs are generated in the gap, thereby dropping the gap resistivity. The photocarriers are accelerated along the direct current bias field and recombine after a short distance. This induces time varying surface currents on the device structure, which in turn produces a propagating THz pulse with an electric field [6]. To maintain high terahertz generation, it is necessary to avoid heating of the semiconductor due to increasing thermal conductivity and disrupting the carrier acceleration. As a result of which, the bias and optical power has to be optimized for the material without damaging the emitter to the levels at which electric breakdown or optical damage can occur.

The THz pulse energy is derived from static bias field [7]. Generation of the THz radiation is associated with the properties of the material used. There is a widespread agreement amongst the researchers that for PCA emitter or detector to exhibit broadband performance, the photoconductive material must have short carrier lifetime (≈picosecond). However, low carrier lifetime is one of many properties that govern the performance of a material. Other aspects such as higher carrier mobility, wideband gap, higher breakdown voltage, reduction of zero bias photocurrent and optimization the material dark resistivity affect the performance of PCA such as output power, bias voltage, bandwidth, and signal to noise ratio [8].

In this review article, we aim to bring together the research carried out on materials used for PCA devices and their role inefficient THz generation. The choice of the material is based on their wide use with a focus on the experimental work.

## 2. PC materials for THz generation

The development of spectroscopy and imaging system has been possible due to the ease of fabrication with lithography and availability of cheaper substrate material such as GaAs having pico second response. GaAs is the most researched and comprehended compound semiconducting material. It has been proven indispensable for many device applications — from ultra-high-speed transistors to lasers and solar cells.

For THz generation, a typical PCA structure has a dipole antenna with a large gap and it has been observed that there exists a strong field enhancement in proximity of the anode. Salem et al. [9]have reported that the amplitude of THz emission can be raised to very higher values when the precisely focused laser beam is moved to the anode of an ion-implanted GaAs antenna at the same bias voltage.

It's well known that intrinsic GaAs has high attenuation and dispersion at THz frequencies. The devises which operate in THz frequency range such as GaAs implanted with H+, N+, O+, and As+ ions have been extensively studied by various researchers [10, 11, 12]. Intrinsic defects in GaAs (refer to figure 1 for crystallographic structure) consists of both As and Ga vacancies. Their concentration is estimated by the overpressure of As during processing. GaAs substrate can be treated to form a semi-insulating (SI) and low-temperature (LT) substrate. Devices made of SI-GaAs by ion implantation are self-isolating, and therefore SI-GaAs becomes a promising material for integrated circuit fabrication. LT-GaAs is another popular choice which has a lifetime as short as 1−10 ps and at the same time possesses high mobility of approximately 120-150 cm$^2$/V. s [13].

The main causes behind the described properties are linked to the creation of structural defects during the growth and annealing procedures. These defects play an important role of deep centres thereby yielding short lifetime of charge carriers [14]. Selection of an appropriate substrate material is made on the basis of short recombination time (≈100 ps for SI GaAs and<1 ps for LT GaAs). Consequently, for LT-GaAs, short carrier lifetime is mainly responsible for higher breakdown dc voltage, lower dark current and suitability the material for use as emitter and detector [15, 16].

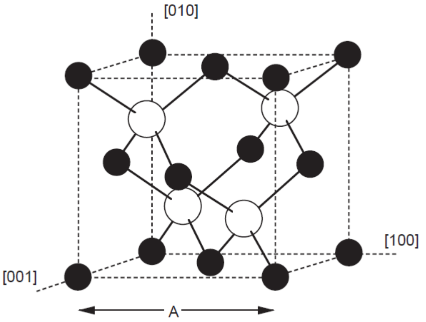

**Figure 1:** Unit cube of GaAs crystal Lattice with crystallographic orientations [17]

Care should be taken to keep the temperature of the semiconductor material low to avoid the increase in thermal conductivity. Semi-insulating GaAs has very few electrons and holes because it has very few dopant atoms. To keep high THz emissions, it is essential to avoid the heating of semi-insulating material which could lead to increasing thermal conductivity and disruption of the carrier acceleration. LT-GaAs is a good material because it produces less heating owing to its low carrier mobility which results in lower photocurrent. Emitters based on SI-GaAs yield strong signals in comparison to LT-GaAs and ion implanted semiconductors. However, because of low dark current one can operate LT-GaAs at high bias voltages when excited with higher laser power.

Various research groups [18] have shown keen interest in semiconductors like Fe-implanted InGaAs and LT-InGaAs, which could be excited with relatively strong fiber-based lasers. The main challenge for the development of InGaAs-based photoconductors is smaller band gap which results in larger dark background conductivity and lower breakdown field strength. Kirill Kuznetsov et al. [19] have reported the Hall effects measurements on spiral antenna topology PCA with InGaAs heterostructures using van der pauw method (Table 1). The electron sheet concentration and mobility depends upon the heterostructure design and the substrate orientation. The research group further studied the carrier density using pump-probe technique and observed that the rise in the radiation power is linked to the increase in counts of anti-structural defects.

**Table 1:** Electronic mobility and sheet concentration in photoconductive hetero-structures [19]

| Sample | $n_s$ ($10^{12}$cm$^{-2}$) | μ (cm$^2$/Vs) |
|---|---|---|
| LT-InGaAs/GaAs (100) | 11.9 | 380 |
| LT-InGaAs/GaAs (111) A | 20.1 | 110 |
| LT-InGaAs/InAlAs/InP (111) A | 1.2 | 30 |

Williams et al [20] have shown that bulk ErAs: In$_{0.53}$Ga$_{0.47}$As grown using molecular beam epitaxy and designed for sub pico second photoconductivity, shows an exponentially steep rise in the resistivity at temperatures less than 250 K (figure 2). This increased resistivity promises to produce THz PC switches due to the high bias voltage.

The first epitaxial layer was an undoped 0.1-$\mu$m-thick In$_{0.52}$Al$_{0.48}$As buffer layer grown lattice that was matched with a semi-insulating In P substrate. Williams et al [21] used In$_{0.53}$Ga$_{0.47}$Aslattice, matched to1.0 $\mu$m thick In P to take in the major portion of the 1550 nm laser power in a single shot. Er and Be were used as dopants giving an n-type behaviour with a resistivity of 13.1Ωcm, a free electron concentration of 1.2x10$^{15}$cm$^{-3}$, and a mobility of 384 cm$^2$/V. s. A self-complementary square spiral was fabricated and was used to exhibit higher THz power and optical conversion efficiency in ErAs: GaAs at 780 nm [22].

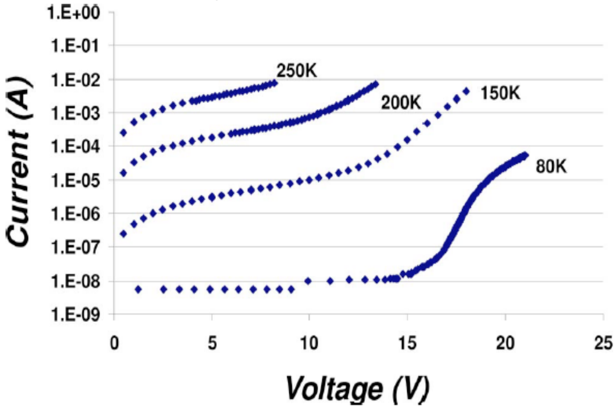

**Figure 2:** I–V curves of the ErAs: In0.53Ga0.47As device at 80, 150, 200, and 250 K when there was no incident laser power [21].

Upcoming materials for PCA are plasmonic nanostructures which enhance the electric field of an ultrashort pulsed pump beam at localized surface plasmon resonance (LSPR). Enhancement of this local field further increases the production of photo carriers and THz pulse emission from the PCA. Sang-Gil Park et al. [23] have developed a nanoplasmonic photoconductive antenna (NP-PCA) with metal nanoislands. The basic concept behind high THz generation from a PCA is to increase the effective excitation area as depicted in Figure.3. The figure shows a schematic diagram of NP-PCA which has large area for excitation. Metal nanoislands serve as plasmonic nanoantennas over the entire photoconductive area for localizing the pump beam. The increase in this large-area local field of the pump beam is responsible for the enhancement of the emission of THz pulse. It is worthwhile to mention here that the photoconductive area with plasmonic nanostructures has to be kept at lower side because the nanofabrication of metal nanostructures such as e-beam lithography is very expensive.

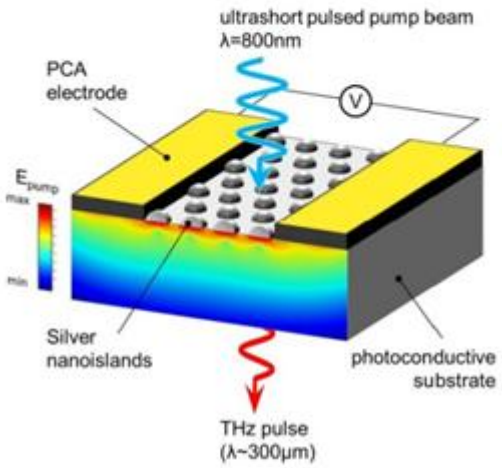

**Figure 3:** Large-area nanoplasmonic PCA with 800nm pump excitation [23]

Sang-Gil Park et al. [23] fabricated Ag nano islands of 174nm diameter at wafer-level with the help of thermal de-wetting of thin Ag film. The PCA with plasmonic nano islands shows two times higher THz pulse emission power compared to a conventional bow-tie PCA. It is worth noting that Ag nanoislands concentrate light between the islands instead of direct illumination of the substrate. The increase in local field is mainly responsible for the increase in photocurrent, though the light concentration decreases the local electric field resulting in low density of carriers. However, it's important to note that the total photocurrent remains unaffected due to low density of carriers below Ag nanoislands. This is because of the fact that Ag nanoislands act as an ideal conductor in the biased electric field.

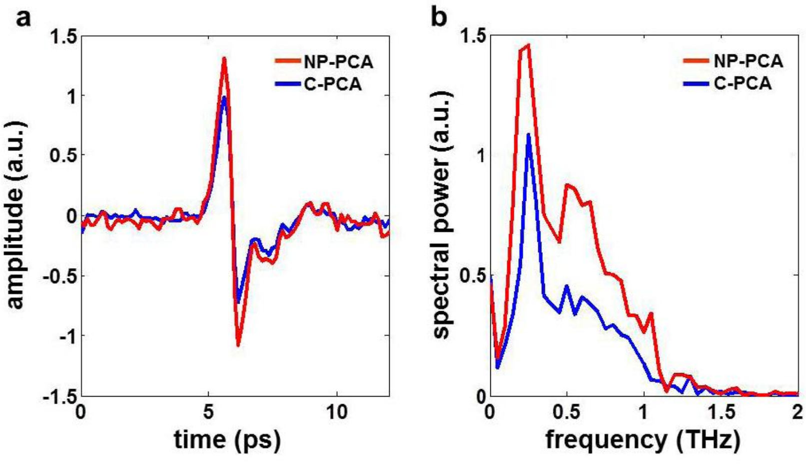

**Figure 4:** (a) Time-domain waveforms and (b) spectral power of THz pulses emitted from NP-PCA with Ag nano islands and a conventional PCA (C-PCA) [23]

The average emission power is increased by two times over 0.1-1.1 THz bandwidth as shown in figure 4 [23]. Graphene has also been explored as a potential THz source with patch antenna geometry supporting plasmonic modes in THz range. Moreover, the electronic properties of the graphene layer can be tuned by its chemical potential, which could lead to tunable resonant antennas over a wide range of frequencies [24]. Based on simulation studies, the graphene based PCAs claim to resolve the issue of impedance matching between incident pump beam and metallic antennaand limited bandwidth due to high performance only in a narrow band of frequencies. Such properties may be used favourably to overcome the above-mentioned challenges in the PCAs, by replacing the metallic antenna part with that made of graphene layers [25]. Koohi et al [26] proposed a design guide for a dipole-like PC antenna that consists of graphene sheets and photonic photmixer in the centre of the gap. The photonic mixer consists of a thin layer of an ultra-fast photoconductor, for example, GaAs (LTG-GaAs) grown at lower temperatures. The photonic mixer, is in fact a combination of two CW infrared lasers in the DC biased fast photoconductive layer which acts as a nonlinear medium.

The resultant photocurrent excites the dipole-like antenna and the antenna radiates waves at the THz beat frequency of the two IR lasers. The simulation work provides promising Graphene-THz future into bendable electrodes; however, graphene as a material has limited commercial availability owning to expensive manufacturing process.

## 3. Conclusion

Recently, there have been efforts to explore semiconductor hetero-structures for photoconductive antenna devices other than conventional GaAs substrate which is still a popular choice for THz generation using an 800nm pump laser. The desire to explore other materials has been due to the advancement in fibre laser technology comprising of a compact setup and emitting a short wavelength of 1500nm. This review paper covers the latest research on material technology for PCA devices highlighting differences between semi-insulating and low temperature GaAs and their usability in developing integrated THz electronics. The review article also provides key results on InGaAs which is an upcoming material that can be used with fibre oscillators. Materials that can be used to investigate the plasmonic effects at THz frequencies and fabrication of THz patch antenna using Graphene, is fairly a new concept. Therefore, this area needs more experimental work on device manufacturing, the radiation intensity and signal-to-noise ratio.

## References

[1] Bang Wu, Lei Cao*, Zhang Zhe, Fu Qiang, Yongqian Xiong, “Terahertz Electro-Optic Sampling in Thick ZnTe Crystals below the Reststrahlen Band with a Broadband Femtosecond Laser”, IEEE Transactions on Terahertz Science and Technology, 99, 1, 2018

[2] G. Mourou, C. V. Stancampiano, A. Antonetti, and A. Orszag, “Picosecond microwave pulses generated with a sub picosecond laser-driven semiconductor switch”. Appl. Phys. Lett.39, 295 (1981)

[3] D. H. Auston, K. P. Cheung, and P. R. Smith. “Picosecond photoconducting Hertzian dipoles” Appl. Phys. Lett.45, 284 (1984)

[4] J. T. Darrow, B. B. Hu, X.-C. Zhang, and D. H. Auston, “Subpicosecond electromagnetic pulses from large-aperture photo conducting antennas” Optics Letters, 15, 323-325 (1990)

[5] Afshin Jooshesh, Levi Smith, Mostafa Masnadi-Shirazi, Vahid Bahrami-Yekta, Thomas Tiedje, Thomas E. Darcie, and Reuven Gordon “Nanoplasmonics enhanced terahertz sources”. Optics Express Vol.22, 27992-28001 (2014).

[6] P. K. Benicewicz, J. P. Roberts, and A. J. Taylor, “Scaling of terahertz radiation from large-aperture biased photoconductors, ” J. Opt. Soc. Am. B 11, 2533–2546 (1994)

[7] Wei Shi, Lei Hou, and Xinmei Wang, “High effective terahertz radiation from semi-insulating-GaAs photoconductive antennas with ohmic contact electrodes” Journal of Applied Physics 110, 023111 (2011)

[8] Nathan M. Burford and Magda O. El-Shenawee. “Review of terahertz photoconductive antenna technology“. Optical Engineering, 56, 010901 (2017)

[9] B Salem, D Morris, V Aimez, J Beerens, J Beauvais and D Houde, “Pulsed photoconductive antenna terahertz sources made on ion-implanted GaAs substrates”, J. Phys. Condens. Matter 17, 7327, (2005)

[10] M. Mikulics, “Traveling-wave photo mixers fabricated on high energy nitrogen-ion implanted GaAs”. Appl. Phys. Lett.89, 071103 (2006)

[11] Tze-An Liu, “THz radiation emission properties of multienergy arsenic-ion-implanted GaAs and semi-insulating GaAs based photoconductive antennas” J. of Appl. Phys.93, 2996 (2003)

[12] J. U. Kang and M. Y. Frankel, “Ultrafast carrier trapping in oxygen-doped metal-organic vapor phase epitaxy GaAs”. Appl. Phys. Lett.70, 1560 (1997)

[13] S. Gupta, M. Y. Frankel, J. A. Valdmanis, J. F. Whitaker and G. A. Mourou, “Subpicosecond career lifetime in GaAs grown by molecular beam epitaxy at low temperatures”. Appl. Phys. Lett., 59, 3276, (1991)

[14] F. W. Smith, H. Q. Le, V. Diadiuk, M. A. Hollis, and A. R. Calawa, “Picosecond GaAs-based photoconductive optoelectronic detectors” Appl. Phys. Lett.54, 890 (1989)

[15] S. Kasai, M. Watanabe and T, Ouchi, “Improved terahertz wave intensity in photoconductive antennas formed of annealed low temperature grown GaAs”. Jpn. J. Appl. Phys., 46, 4163, (2007).

[16] L. Hou and W. Shi, “An LT GaAs terahertz photoconductive antenna with high emission power, low noise, and good stability” IEEE Trans. Electron Devices, 60, 1619 (2013).

[17] Kayali, S. “GaAs material properties“ JPL Publication, 96, 25. (2006).

[18] Winnerl, S., Peter, F., Nitsche, S., Dreyhaupt, A., Zimmermann, B., Wagner, M., Schneider, H., Helm, M. and Kohler, K., “Generation and detection of THz radiation with scalable antennas based on GaAs substrates with different carrier lifetimes.” IEEE Journal of Selected Topics in Quantum Electronics, 14, 449. (2008).

[19] Kuznetsov, K. A., Galiev, G. B., Kitaeva, G. K., Kornienko, V. V., Klimov, E. A., Klochkov, A. N., Leontyev, A. A., Pushkarev, S. S. and Maltsev, “Photoconductive antennas based on epitaxial films In0.5Ga0.5As on GaAs (1 1 1) A and (1 0 0) substrates with a metamorphic buffer”. Laser Physics, 28, 076206, (2018)

[20] E. R. Brown, Kimani K. Williams, W. Zhang, J. Suen, H. Lu, J. Zide and A. C. Gossard, ” Electrical transport in a semimetal-semiconductor nanocomposite” IEEE Trans. Nanotechnol.8, 402, (2009).

[21] Kimani K. Williams, Z. D. Taylor, J. Y. Suen, Hong Lu, R. S. Singh, A. C. Gossard, and E. R. Brown, “Toward a 1550 nm InGaAs photoconductive switch for terahertz generation”, Optics Letters 34, 3068, (2009)

[22] Z. D. Taylor, E. R. Brown, J. E. Bjarnason, M. P. Hanson, and A. C. Gossard, “Resonant-optical-cavity photoconductive switch with 0.5% conversion efficiency and 1.0W1.0W peak power” Optics Letters Vol.31, 1729, (2006)

[23] Sang-Gil Park, Yongje Choi, Young-Jae Oh, and Ki-Hun Jeong, “Terahertz photoconductive antenna with metal nanoislands” Optics Express 20, 25530, (2012)
[24] Nissiyah, G. J. and Madhan, M. G., “Graphene based microstrip antenna for triple and quad band operation at terahertz frequencies“Optik, 231, 166360, (2021)
[25] Tamagnone, M., Gomez-Diaz, J. S., Mosig, J. R. and Perruisseau-Carrier, “Reconfigurable terahertz plasmonic antenna concept using a graphene stack” Appl. Phys. Lett.101, 214102 (2012)
[26] Koohi, M. Z. and Neshat, M., 2015. Evaluation of graphene-based terahertz photoconductive antennas. Scientia Iranica. Transaction F, Nanotechnology, 22, 1299, (2012)