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Vertical versus planar pulsed photoconductive antennas that emit in the terahertz regime

E. Moreno [a,*], R. Sohrabi [b], G. Klochok [c], E.A. Michael [a]

[a] Photonics Group, University of Chile, Chile
[b] Malek Ashtar University Of Technology, Isfaham, Iran
[c] Moscow State University Of Civil Engineering

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ABSTRACT

The design process of a photoconductive antenna (PCA), which emits efficiently in the electromagnetic terahertz range, demands some considerations that are discussed through this work. In this work, several essential characteristics of a photoconductive antenna made with LT-GaAS are studied by means of well established commercial software (COMSOL 5.3 [1]). An approach to the efficiency is also made through the study of geometry, the laser illumination position, the substrate doping distribution, the direction of the bias applied to the semiconductor, the matching impedance at the laser operating frequency and, finally, the plasmonics effects or penetration laser enhancement due to the use of nano antennas. We study and compare two kinds of structures, one which is quasi-bidimensional or planar and the other which is vertical. Additionally, the photoconductive antennas are also modeled by using a simplified equivalent circuit which helps to understand the antennas' performance. Therefore, some fundamental parameters, like the transient capacitance between the metal contacts are also studied. Furthermore, we introduce an optimized vertical design which achieves the best results.

1. Introduction

Since the first pioneers attempted to accomplish the fabrication of powerful sources that radiate their power inside the terahertz band (0.1–10 THz), the accumulated knowledge has become huge. This fact has enabled great improvement in the area of power emitted in the THz band, although in 2012 the community was still suffering from non-efficient emitters [2].

To mend this, a particular kind of emitter, the so-called photoconductive, has caught the attention of many researchers, who are currently concerned with its efficiency due to its characteristics. One of the most important factors in the building up of efficient terahertz commercial devices is simplicity, which means a non-prohibitive cost. From this point of view photoconductive antennas represent a serious and realistic choice. For instance, simple sputtering techniques have been shown to enhance the efficiency around 7% [5]. In this paper the majority of geometrical features of the antennas studied are bigger than those explained in [5], so atomic layer deposition is not indispensable in our designs. However, the geometry and features of materials which compose the vertical structures could be fabricated by taking advantage of atomic layer deposition techniques.

* Corresponding author.
E-mail address: enrique@moreno.ws (E. Moreno).

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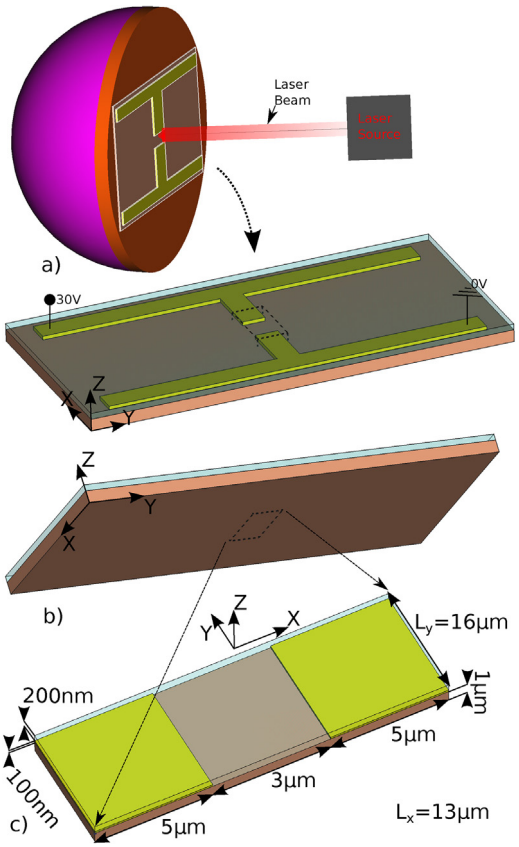

Fig. 1. (a) An entire planar PCA. (b) The figure corresponds to the part of a PCA which experiments the photoelectric effect (called photo-zone [3]). It is a composition of a semiconductor substrate, deposited metal contacts on that substrate and a layer of air that covers this photo-zone. (b) In [4] clearly shows what part of the PCA is commented in here. (c) Likewise the figure taken from the photo-zone denotes the particular area where the laser impinges the semiconductor and where the strongest photocurrent occurs. This is the gap between the metal contacts that bias the semiconductor, the core of the antenna. (The figures are not drawn to scale.)

In the present manuscript, aiming to investigate efficiency, we analyze the laser absorption rate into the semiconductor. Therefore, we exploit the plasmonics effects. These effects were a significant breakthrough [6] which permit a higher level of laser absorption in the semiconductor. Another meaningful parameter which has been considered here is a non-uniform doping distribution in the semiconductor [7,8]. In particular, unitraveling-carrier (UTC) photodiodes which are devices that employ an innovative distribution of the doping [7]. In the frequency domain, the UTCs play an important role because they can increase the higher frequency components that compose the photocurrent [7] and, consequently, the desirable frequencies which constitute the radiated field (Maxwell equations are linear). Moreover, the photo-Dember mechanism [9] is also taken into consideration.

A PCA is a non-linear device. Thus there are two types of impedance matchings. One is given by the antenna geometry and lens characteristics in order to improve the emission in the terahertz range and the other enhances the laser transmission into the semiconductor. The other is responsible for an intensification of the photoelectric effect and therefore the photocurrent. Accordingly anti-reflective coating has also been included in the vertical PCAs. Just the ones which show the best performance.

In addition, some publications that look upon the potential of plasmonics effects for enhancing the quantum efficiency of conventional ultrafast photoconductors do not take into account the electric bias direction of the semiconductor versus the laser focus spot position [10,11]. In [10] as well as in [11], Fig. 1 of these publications shows how the laser spot on the semiconductor is applied close to the anode. In those publications, the substrate was a uniform doping semiconductor, LT-GaAs. The photocurrent is obviously driven by holes or by slow electrons. This misconception is discussed here and the electric bias direction of the semiconductor versus the laser focus position is analyzed too.

Last but not least, the screening phenomenon [8] is scrutinized by virtue of the time dependent capacitance along the transient state. We make use of an equivalent circuit which helps to visualize and understand this phenomenon.

Figs. 1 and 2 illustrate both kinds of geometries studied. Their details are explained in Section 2.1. The paper has been structured in five sections. In Section 2 the computational domain under study is introduced together with all the parameters needed in the simulations carried out. In Section 3 all the simulations carried out along with an explanation that justifies them are described. Also, we compare the choice with several ones taken from literature in order to enrich our contribution. The