Analysis of Black Phosphorus Terahertz Photoconductive Antenna

Jose Santos, M. Hasan Doha,
Hugh Churchill, and Magda El-Shenawee
University of Arkansas
Fayetteville, AR, United States
jisantos@uark.edu, mdoha@uark.edu,
hchurch@uark.edu, magda@uark.edu

Nathan M. Burford
WattGlass, Inc.
Fayetteville, AR, United States
nathan@wattglass.com

***Abstract*—This paper presents a parametric analysis of a photoconductive antenna that implements the 2-D material black phosphorus (BP). This material fills the gap between the electrodes of the antenna. The study involves modeling and simulation of the device using COMSOL Multiphysics at different bias voltages. We present the calculations of the photocurrent density versus time at the center of the gap in the BP layer, and the maximum photocurrent density value measured over time for multiple bias voltages. The results showed a saturation behavior versus bias voltage.**

***Keywords*—terahertz; black phosphorus; photoconductive antenna**

I. Introduction

Terahertz photoconductive antennas have gained an increasing importance in the past years due to their numerous applications. Some advances have been directed towards the improvement of the laser power absorption, carrier dynamics of the semiconductor, and efficiency of these optoelectronic devices. For instance, previous work of our group has been focused on the application of plasmonic nanodisks for the enhancement of the optical electric field absorption [1]. This enhancement positively impacts the performance of a photoconductive antenna by improving terahertz field emission by five times compared to conventional antennas.

Another approach that researchers have taken is developing new materials to obtain better optical and electrical properties. In this regard, black phosphorus (BP) stands out as a potential candidate for terahertz applications. Black phosphorus is an anisotropic 2D layered material that offers a layer-dependent direct bandgap, high mobility, and short carrier lifetime [2]. Recently, black phosphorus has been implemented in high frequency semiconductor devices applications. However, some of its properties such as carrier mobility and carrier drift velocity have been reported with widely varying values in the literature [2-6]. Hence, there is a level of uncertainty on the material properties that are needed for accurate modeling. This brings the necessity to study this material on a device level under different conditions. The purpose of this work is to model the behavior of black phosphorus terahertz photoconductive antennas and conduct a parametric analysis of its photocurrent response to different bias voltages.

This work was sponsored by the National Science Foundation (NSF) Award # 1948255 and the UA Chancellor Discovery Grant Award.

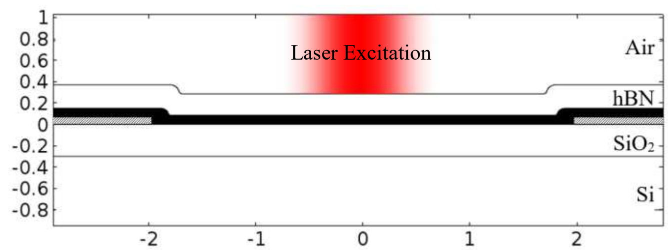

Fig. 1. Simualtion domain with the black phosphorus layer (black) in the center of the antenna gap between the electrodes. Laser excitation shown in red (not at scale) with a 780 nm wavelength, a pulse width of 3 µm, a repetition rate of 80 MHz, and a maximum laser insensity of 4.27 W/µm^2 [1].

II. Methodology

The commercial package COMSOL Multiphysics is implemented to solve a model that combines the absorption of the laser excitation with carrier dynamics of the semiconductor. The simulation domain is described in Fig. 1, where an 85 nm black phosphorus layer (black color layer in Fig. 1) is placed in the gap of the antenna over a layer of silicon dioxide (SiO_2), which covers a thick silicon substrate. A layer of hexagonal boron nitride (hBN) is placed on top of the BP layer to protect it from the ambient conditions. With this configuration, the coupled Poisson's and continuity equations are implemented to model its electrical response as in [1].

$$\nabla \cdot (\epsilon_r \nabla V) = q(n - p - N_D + N_A) \quad (1)$$

$$\partial n,p /_{\partial t} = \mp {}^{1}/_{q} \, \nabla . J_{n,p} - U_{n,p} \quad (2)$$

In these equations, n, p and V represent the electron density, hole density, and electric potential, respectively. They are the unknowns to be solved by the COMSOL software. The factors q and ε_r represent the electron charge and the relative permittivity of the material. N_D and N_A are the donor and acceptor doping concentration, and $J_{n,p}$ with $U_{n,p}$ represent the current density and recombination/generation processes. The carrier mobility is electric field dependent described by the Caughey-Thomas mobility model:

$$\mu_{n,p} = \mu_{in} / \left(1 + \left({}^{\mu_{in} E}/_{v_{sat,n,p}}\right)^{\alpha_{n,p}}\right)^{1/\alpha_{n,p}} \quad (3)$$

In (3), μ_{in} represents the carrier mobility at low electric fields, E is the electric field between the two electrodes, $\alpha_{n,p}$ is a fitting parameter, and $v_{sat,n,p}$ accounts for the carrier saturation drift velocity.

TABLE I. DISCREPANCY IN BLACK PHOSPHORUS PROPERTIES

Parameter	Symbol	BP1	BP2
Electron Mobility	μ_n	1500 $cm^2/V.s$ [3]	100 $cm^2/V.s$ [2]
Hole Mobility	μ_p	5000 $cm^2/V.s$ [3]	850 $cm^2/V.s$ [2]
Electron Saturation Velocity	$v_{n,sat}$	$0.55 * 10^7$ cm/s [4]	$1.0 * 10^7$ cm/s [6]
Hole Saturation Velocity	$v_{p,sat}$	$1.5 * 10^7$ cm/s [5]	$1.2 * 10^7$ cm/s [6]

As stated earlier, there is some level of uncertainty regarding the electrical properties of the material needed to model a device based on black phosphorus. This uncertainty is displayed in Table 1, where different data are obtained from different literature sources for black phosphorus properties. These sets of data are labeled here as BP1 and BP2 to refer to black phosphorus data 1 and data 2. This data represents some of the variables involved in solving (1) and (2). As anticipated, this controversy directly impacts the prediction of the photocurrent generated by the device.

III. RESULTS AND DISCUSSION

With the model described in the previous section, a parametric study is performed over the bias voltage between the antenna electrodes. The bias voltage is varied from 0 to 30 V to a black phosphorus layer described by the BP2 data of Table 1. The photocurrent density response of the black phosphorous is calculated at the center of the antenna gap. Fig. 2a displays the photocurrent density at a bias voltage of 2 V versus time. At this bias voltage, the maximum value of the photocurrent density is experienced around 0.028 A/µm^2. Considering this peak photocurrent density and the laser intensity (4.27 W/µm^2), the responsivity of the photoconductive antenna at this bias voltage is calculated to 6.56 mA/W, representing the photocurrent generated depending on the optical power applied to the device. This responsivity is valid only for low optical power out of the saturation range (Fig. 3 in [1]).

The maximum value of the registered photocurrent density is chosen as a measure of the antenna performance. The plot in Fig. 2b represents the peak of the photocurrent density at every voltage step. This comparison provides an understanding of the response of the black phosphorus against the laser excitation for different bias voltages. From this graph, it is noticeable that at higher bias voltage the peak of the photocurrent density approaches a saturation level. After this level, the magnitude of the current is driven by the increase in the electric field rather than the generated photocarriers. Increasing the bias voltage after this point would not represent a significant increase in the photocurrent density amplitude, and it would bring the risk of breaking down the device.

Calculating the slope of the plot displayed in Fig. 2b is another way of studying this bias voltage dependence of the peak of the photocurrent density. This study is shown in Fig.

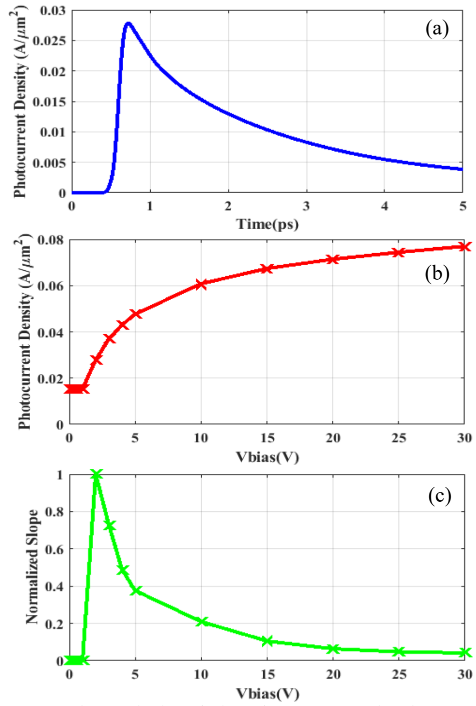

Fig. 2. Parametric analysis of the photocurrent density at multiple bias voltages. (a) Photocurrent density profile over time measured at the center of the gap in the BP layer, (b) Maximum photocurrent density value measured at the center of the antenna gap vs bias voltage, (c) Normalized slope of the maximum photocurrent density plot

2c, which demonstrates the normalized slope of the photocurrent peak density. As it is displayed, the highest increase in the peak of the photocurrent density is obtained at 2 V bias voltage. As the bias voltage is increases, the rate of change of the maximum photocurrent density decreases. Upon looking at Fig. 2c, it can be observed that after 5 V bias voltage, there is no significant increase of the photocurrent peak. The performance of the BP emitter will be measured using a THz time-domain spectroscopy system.

REFERENCES

[1] N. Burford and M. El-Shenawee, “Computational modeling of plasmonic thin-film terahertz photoconductive antennas,” *Journal of the Optical Society of America B*, vol. 33, no. 4, p. 748-759, 2016.

[2] R. J. Suess, E. Leong, J. L. Garrett, T. Zhou, R. Salem, J. N. Munday, T. E. Murphy, and M. Mittendorff, “Mid-infrared time-resolved photoconduction in black phosphorus,” *2D Materials*, vol. 3, no. 4, p. 041006, 2016.

[3] G. Long, D. Maryenko, J. Shen, S. Xu, J. Hou, Z. Wu, W. K. Wong, T. Han, J. Lin, Y. Cai, R. Lortz, and N. Wang, “Achieving Ultrahigh Carrier Mobility in Two-Dimensional Hole Gas of Black Phosphorus,” *Nano Letters*, vol. 16, no. 12, pp. 7768–7773, May 2016.

[4] K. K. H. Smithe, C. D. English, S. V. Suryavanshi, and E. Pop, “High-Field Transport and Velocity Saturation in Synthetic Monolayer MoS2,” *Nano Letters*, vol. 18, no. 7, pp. 4516–4522, 2018.

[5] X. Li, Z. Yu, X. Xiong, T. Li, T. Gao, R. Wang, R. Huang, and Y. Wu, “High-speed black phosphorus field-effect transistors approaching ballistic limit,” *Science Advances*, vol. 5, no. 6, 2019.

[6] X. Chen, C. Chen, A. Levi, L. Houben, B. Deng, S. Yuan, C. Ma, K. Watanabe, T. Taniguchi, D. Naveh, X. Du, and F. Xia, “Large-Velocity Saturation in Thin-Film Black Phosphorus Transistors,” *ACS Nano*, vol. 12, no. 5, pp. 5003–5010, 2018.