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Performance enhancement of Pt/TiO_2/Si UV-photodetector by optimizing light trapping capability and interdigitated electrodes geometry

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ABSTRACT

This paper presents a hybrid approach based on an analytical and metaheuristic investigation to study the impact of the interdigitated electrodes engineering on both speed and optical performance of an Interdigitated Metal–Semiconductor–Metal Ultraviolet Photodetector (IMSM-UV-PD). In this context, analytical models regarding the speed and optical performance have been developed and validated by experimental results, where a good agreement has been recorded. Moreover, the developed analytical models have been used as objective functions to determine the optimized design parameters, including the interdigit configuration effect, via a Multi-Objective Genetic Algorithm (MOGA). The ultimate goal of the proposed hybrid approach is to identify the optimal design parameters associated with the maximum of electrical and optical device performance. The optimized IMSM-PD not only reveals superior performance in terms of photocurrent and response time, but also illustrates higher optical reliability against the optical losses due to the active area shadowing effects. The advantages offered by the proposed design methodology suggest the possibility to overcome the most challenging problem with the communication speed and power requirements of the UV optical interconnect: high derived current and commutation speed in the UV receiver.

1. Introduction

In order to exploit any photodetector in an efficient manner, several performance criteria are preferred for instance the simple and high speed operation simultaneously with high responsivity [1,2]. In this context, several works have been focused on the development and enhancement of photodetectors structures based on Heterojunction Metal-Semiconductor-Metal (HMSM), photoconduction, p-i-n junction [3–5] and Schottky-type contact structures [6]. Among these devices, the MSM PhotoDetectors (MSM-PDs) are very attractive due to their extensive applications in optical fiber communication systems, high-speed optical interconnects and environment monitoring areas [7,8]. Because of the lateral planar geometry of MSM-PDs, small capacitance per unit area is obtained with respect to the standard p-i-n photodiode with an equal active area [9]. Even if the MSM-PD exhibits a very elevated responsivity in the UV region, tens of seconds as response time is too long, and prohibits its application basically when ultrahigh response is needed. The limitation of response time in a conventional

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MSM-PD is mainly due to the transit time of the photo-generated carriers. The most common way to increase the photodetector speed is by scaling down the spacing between the interdigital contacts and the overall dimensions of the MSM-PD [10–12]. Nevertheless, such decrease in the interelectrode spacing decreases the active area, thus leading to the degradation of the photodetector sensitivity. This in turn, causes the smaller area devices to be intractably aligned and used in optical communication applications.

In order to guarantee a MSM-PD with a satisfactory efficiency, it is crucial to get as large as possible illuminated area. Large area detectors are most appropriate for the fabrication of semiconductor UV detectors and really alleviate the fabrication development constraints [13]. Photodetector with large light detected area would allow the use of multimode step-index fibers and supply the advantages of improved coupling efficiency [14]. Thus, the IMSM-PD with fork shaped electrodes has been proposed as an alternative design for photodetector applications. Such design choice is justified by their better properties like the large active area and the high response time over the MSM-PD including two square shaped electrodes in addition to its flexibility of integration using CMOS technology [15]. Moreover, the IMSM-PD is considered as a powerful tool for photodetector applications, the unexpected degradation of IMSM-PD performance generated by the shadowing effect remains a critical drawback that we have to overcome using new approaches. In this extent, it is worthy to find a compromise between response time and optical performance. Consequently, different scientific endeavors presented in numerical and experimental studies have been elucidated in order to improve the photodetector performance in terms of optical behavior and commutation speed. In this context, F. Hossein-Babaei et al. [16] have proposed a new UV sensor with response time equals to 17 ms. Xie et al. [17] have fabricated an UV photodetector based on TiO_2 nanorod with 150 ms response time. A.M. Selman et al. [18] have reported the response time of UV sensor based on rutile TiO_2 nanorod as 20 ms value under 365 nm UV light illumination. However, merely a small number of analytical investigations have been suggested accounting for the interdigitated contact design parameters effect. To the best of our knowledge, no investigations have been carried out for improving both photoresponsivity and commutation speed by optimizing both the interdigitated Schottky barrier geometry and light trapping capability. For that reason, it is a paramount requirement to develop compact analytical models which describe the MSM-PD reliability performance including the interdigitated geometric system impact. This paper presents two stage investigation frameworks of a new IMSM-PD design methodology dedicated to high-speed communication applications. To this extent, new contributions namely electrode engineering aspect and analytical modeling concept are adopted as two promising features to develop new methodology approach based on metaheuristic investigation to study the impact of the interdigitated electrodes engineering on both speed and optical performance of an IMSM-UV-PD. As a first step, compact models for the proposed design especially the photocurrent and the response time are deduced from the analytical solution of coupled Poisson-continuity equations. In the second step, the developed analytical models are used in the context of a MOGA-based approach in order to optimize the geometrical shape of the interdigitated contact system. Consequently, the main objective is to achieve the highest speed commutation and optical performances of the IMSM-PD by boosting the device immunity against the shadowing and optical losses effects. The comparison held with respect to other structures (IMSM-UV-PD, MSM-PD, and conventional design) shows clearly that our proposed design outperforms significantly the other two counterparts, where the proposed design exhibits excellent ability in improving the speed commutation. This result makes the proposed design a potential candidate to high-speed wireless communication systems.

The organization of the paper is as follows. Firstly, we introduce an analytical modeling of the IMSM-PD to investigate the response speed commutation and the photocurrent density behavior. Then, the simulation results are highlighted and discussed in comparison with the experimental data. Finally, we conclude this study by some remarks and perspective research directions.

2. Analytical modeling

In what follows, we develop new analytical models which describe the photodetector behavior including the interdigitated electrodes engineering aspect.

2.1. Modeling of the response time

The structure of the IMSM-PD used in our study is shown in Fig. 1. From top to bottom, it consists of alternating metal contacts deposited on the TiO_2 and Si substrate at the rear side of the structure. In Fig. 1-a, the variables S and W represent the spacing and the width of the fingers, respectively. The parameter L refers to the MSM-PD receiving aperture and d presents the TiO_2 thickness. The MSM-PD interdigitated contact system revealed in Fig. 1-a offers a great opportunity to achieve a short response time without altering the device efficiency. The limitation of response speed of the MSM-PD is mainly due to the transit time of the optically generated carriers and the RC- time constant of the interdigitated diode structure. In general, downsizing the distance along with the fingers reduces the transit time of the optically generated carriers. The key factor that governs the transit time is mainly the carriers' drift velocity and implicitly the electric field inside the active region of the MSM-PD, between the fingers of the metalized area.

Since the field through the intrinsic region of the MSM-PD should be sufficiently high in order to guarantee the carrier drift at near saturation velocities [19,20], this region should be entirely depleted. By taking into account these conditions the transit time is given by Refs. [19–21]: