

Simulation studies of p-doped ZnO MSM Photodetector with Plasmonic Enhancement

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Abstract. This paper presents the simulation studies of Metal-Semiconductor-Metal (MSM) Photodetector (PD) with and without plasmonic enhancement. The simulations were carried out using COMSOL Multiphysics® software. The semiconductor layer was p-type ZnO with a doping concentration of $10^{16}/\text{cm}^3$. The plasmonic layer was of Au nanoparticles. The PD was irradiated with 10W UV radiation of wavelength 280nm. The output currents of MSM PD with and without plasmonic layer were found to be $\sim 0.9 \times 10^{-7}\text{A}$ and $\sim 0.8 \times 10^{-8}\text{A}$ respectively. It was observed that there is an appreciable increase (factor of 10) in photo current in devices with a plasmonic layer. The effect of change in the size of Au nano particles on output photocurrent was also studied.

1. Introduction

UV photodetectors have a number of applications like missile plume detection, determination of pollution levels in air, UV astronomy, ozone layer monitoring, fire alarm systems, spatial optical communications etc. MSM photodetectors have been studied extensively due to their fundamental advantages such as simple structure, ease of fabrication and integration and low capacitance per unit area [1].

The use of Schottky MSM detectors for detection of UV radiation have been reported [2,3]. An increased responsivity (25 times) of an MSM Photodetector with Al nanoparticles has also been reported [4].

In this study, p-doped Zinc Oxide (ZnO) has been chosen as the photo-detecting material. ZnO has a wide bandgap of 3.34eV at room temperature and a binding energy of 60eV. This makes it very suitable for photo-detection working in the UV-A region of 320 to 400nm. ZnO nanostructures have unique advantages including high specific surface area, low toxicity, chemical stability, electrochemical activity, and high conductivity. Both As and Sb which have low acceptor-ionization energies, can be used as a dopant to obtain p-type ZnO [5].

This study focuses on obtaining high photocurrent by developing and simulating models of MSM Photodetectors with and without Plasmonic layer. The variations of photocurrents with change in size of Au nano particles of plasmonic layer is studied and reported. The device will be fabricated after optimization of various layouts and properties.



2. MSM design and simulation

Simulation studies were done on (a) Simple Metal-Semiconductor Schottky Diode (b) MSM PD and (c) MSM PD with plasmonic layer.

2.1. Metal-Semiconductor Schottky Diode

A Ni/p-ZnO Schottky diode was modelled as shown in Figure 1(a). The semiconductor was doped with an acceptor concentration of $10^{16}/\text{cm}^3$. The dimensions were taken as $9 \times 7 \mu\text{m}$.

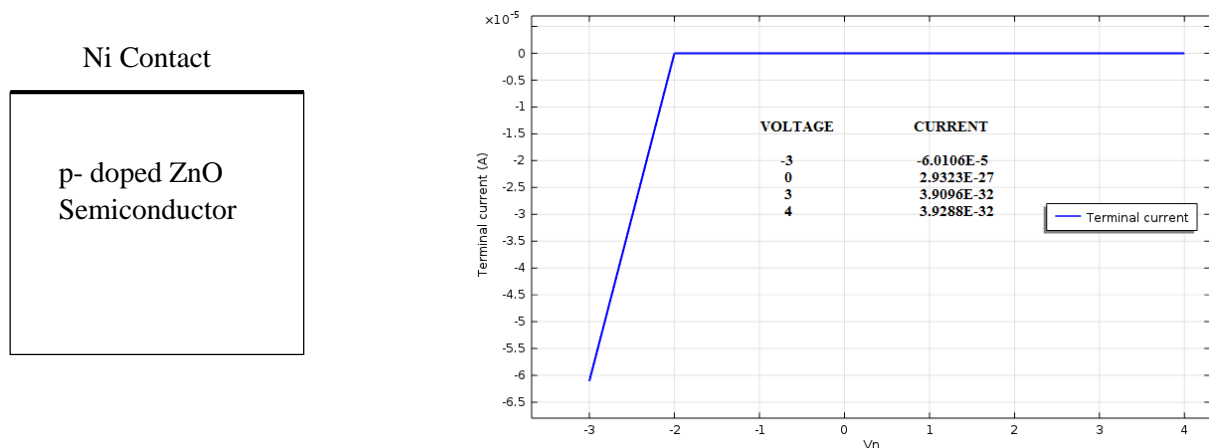


Figure 1(a). Design geometry of p-doped ZnO Schottky diode.

Figure 1(b). I-V characteristic of Ni/p-ZnO Schottky diode.

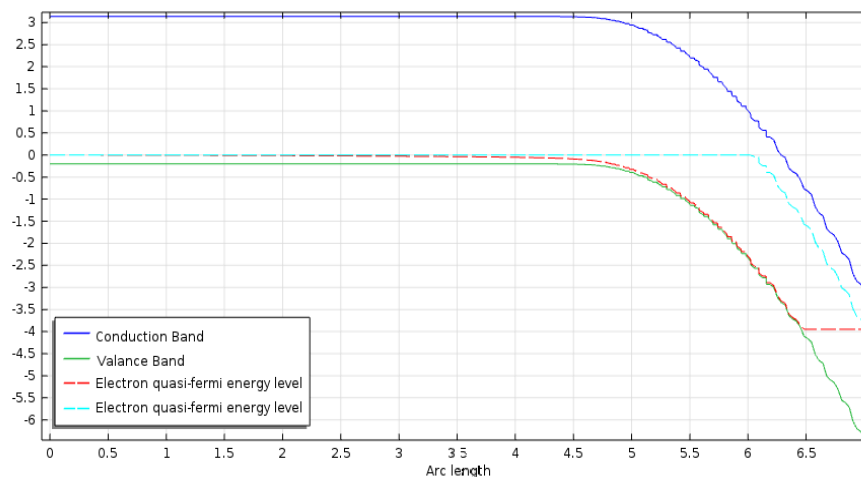


Figure 1(c). Band diagram of Ni/p-ZnO Schottky diode.

Figure 2 shows the IV Characteristics of the diode. It showed increase in output current with increase in input voltage. The output current is $\sim 3.9 \times 10^{-32} \text{A}$ at 4V.

Figure 3 shows the band diagram of the diode and it was in agreement with the band diagram available in literature [6].

2.2. MSM Photodetector

Figure 2(a) shows the cross sectional view of the MSM Photodetector. The dimensions of the device were $9 \times 7 \mu\text{m}$. The finger width and spacing was taken as $3 \mu\text{m}$. The incident wavelength was set at 280nm and the incident power from UV source was set at 10W. All other parameters were kept unchanged.

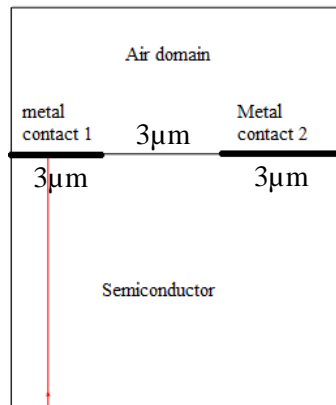


Figure 2(a). Design geometry of Ni/p-ZnO MSM photodetector.

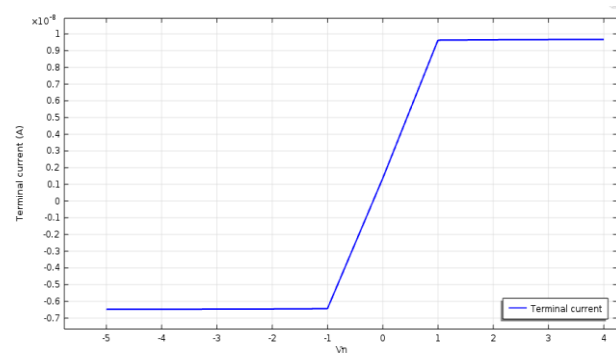


Figure 2(b). *I-V* characteristics of Ni/p-ZnO MSM photodetector.

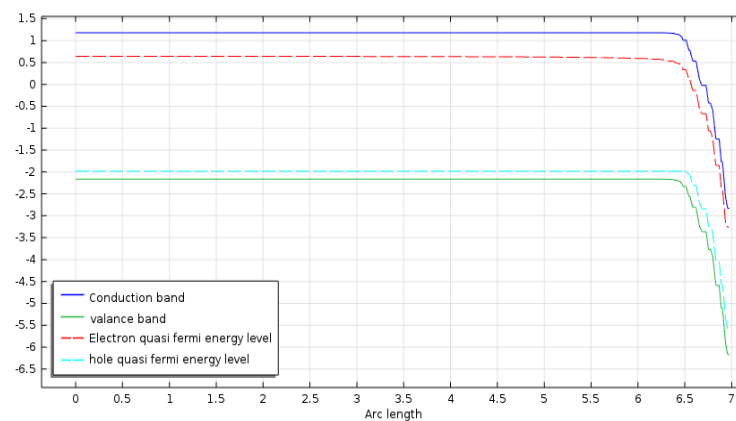


Figure 2(c). Band diagram of Ni/p-ZnO MSM photodetector.

Figure 2(b) shows the IV Characteristics of the MSM photodetector. A large increase in photocurrent is observed in the presence of UV radiation of 280nm. The maximum output photocurrent was found to be $\sim 1 \times 10^{-8}$ (A).

Figure 2(c) shows the band diagram of MSM Photodetector. It was observed that it matched the band diagram of p-doped ZnO from literature [6].

2.3. MSM photodetector with plasmonic layer

A plasmonic layer of gold nano particles was added to the MSM photodetector and various trials were performed on the same.

Figure 3(a) shows the construction of a plasmonic layer based MSM Photodetector. Studies were done with different sizes of Au nanoparticles and with different doping concentrations. The sizes were taken as 50nm and 100nm. The doping concentrations were $10^{16}/\text{cm}^3$ and $10^{20}/\text{cm}^3$.

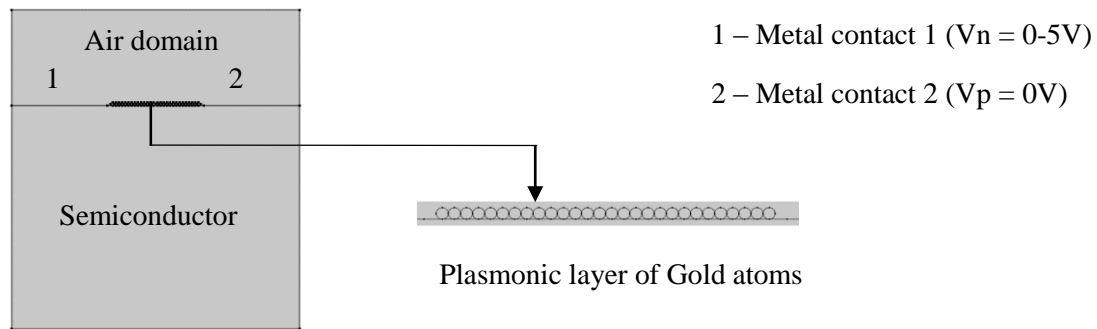


Figure 3(a). Model geometry of MSM photodetector with plasmonic layer.

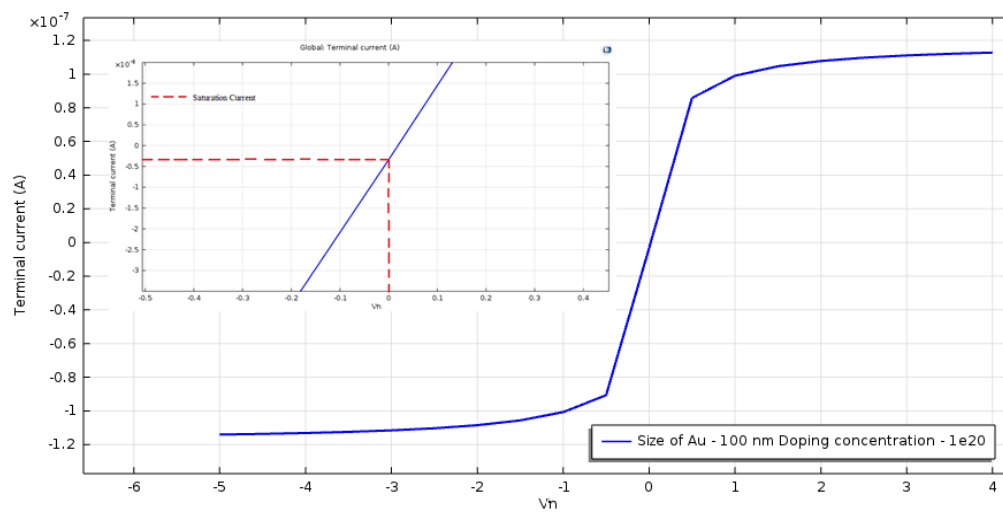


Figure 3(b1)

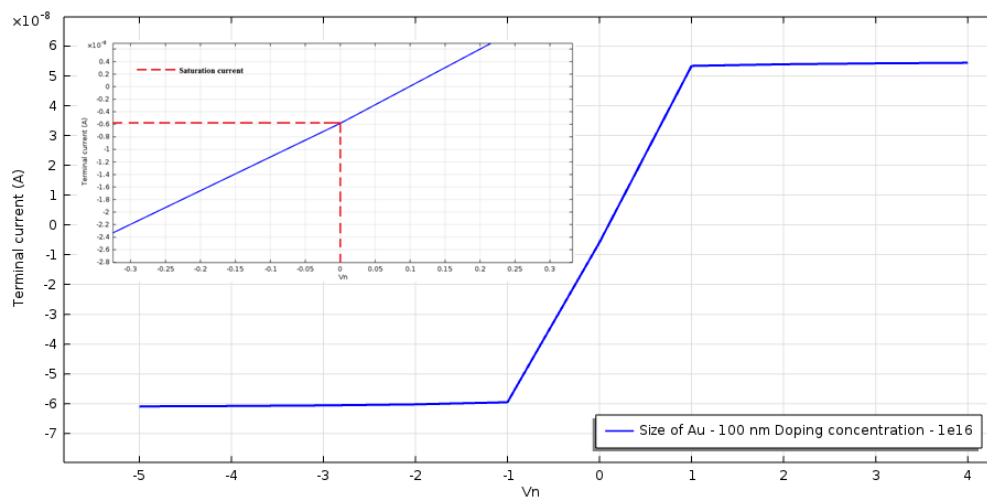


Figure 3(b2)

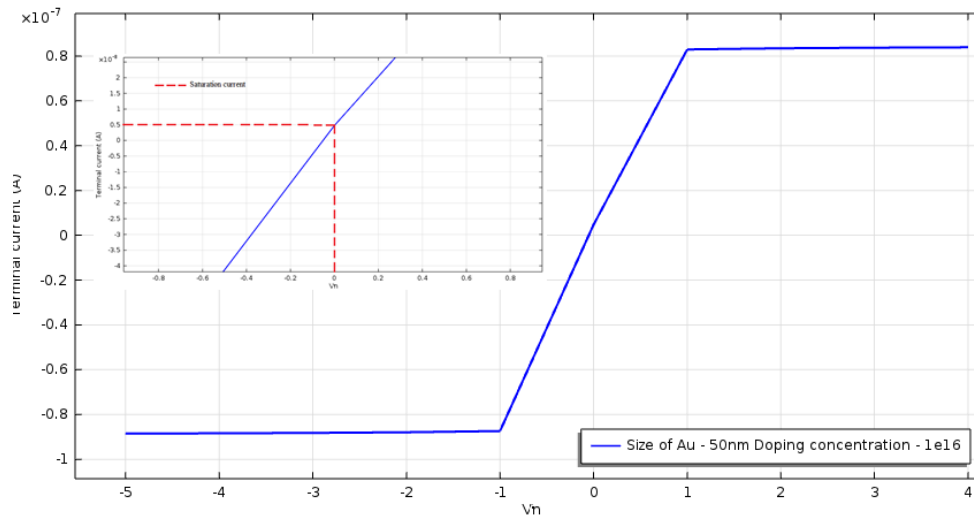


Figure 3(b3)

Figure 3(b) *I-V* characteristic of Ni/p-ZnO MSM PD with plasmonic layer, with varying acceptor concentration and Au particle size. Inset shows I_o .

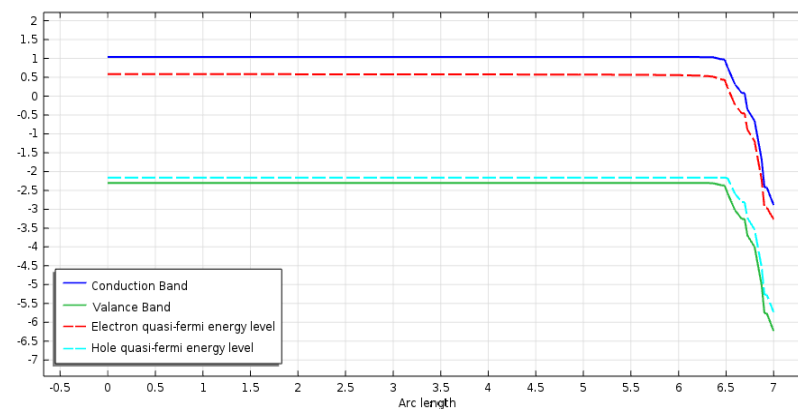


Figure 3(c) Band diagram of p-doped ZnO MSM Photodetector with plasmonic layer.

3. Results and discussion

The IV characteristics obtained in this study are compared with the data available in literature and is shown in figure 4.

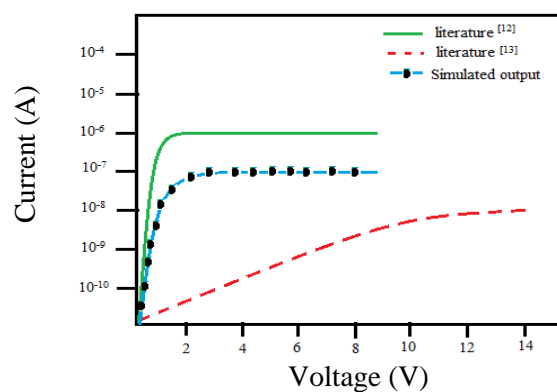


Figure 4. Comparison of the *I-V* characteristic obtained in the simulation study of MSM PD with plasmonic layer, with the literature [7,8].

3.1 Ideality factor and barrier height

The ideality factor of a diode is a measure of how closely the diode follows the ideal diode equation. Rectification in metal-semiconductor junctions can increase the ideality factor to values greater than 2. Values as high as $\eta = 7$, have been found for GaN/GaInN diodes [9,10].

For a Metal-Semiconductor Schottky barrier diode it is assumed that the current is due to thermionic emission, and is given as [11,12]:

$$I = I_o \exp\left(\frac{qV}{\eta kT}\right) [1 - \exp\left(-\frac{qV}{kT}\right)] \quad (1)$$

where I is the total current, I_o is the reverse saturation current, η is the ideality factor, T is the temperature in Kelvin (293K), q is the electronic charge, k is the Boltzmann constant, and V is the applied bias (1V).

At voltages $V \gg 3\frac{kT}{q}$, equation (1) can be written as

$$I = I_o \exp\left(\frac{qV}{\eta kT}\right) \quad (2)$$

$$\therefore \ln I = \ln I_o + \left(\frac{qV}{\eta kT}\right)$$

$$\eta = \left(\frac{q}{kT}\right) \left[\frac{dV}{d(\ln I)}\right] \quad (3)$$

The ideality factor η can be determined from figures 3(b1), 3(b2) and 3(b3).

The barrier height ϕ_{Bp} is given by [12]:

$$\phi_{Bp} = \frac{kT}{q} \ln\left(\frac{A^* T^2}{I_o}\right) \quad (4)$$

where A^* is the Richardson constant of p-ZnO (96A/cm²/K²).

The barrier height was also computed and the results are presented in table 1.

Table 1. Ideality factor and barrier height of MSM Photodetector with plasmonic layer

Size of Au atoms (nm)	Dimensions of the device	Concentration of Acceptor doping (/cm ³)	Total output I (A)	Ideality factor	Saturation current (A)	Barrier height (eV)
50	9x7μm	10 ¹⁶	~ 0.9x10 ⁻⁷	0.8	0.4x10 ⁻⁸	0.88
100	9x7μm	10 ¹⁶	~ 0.5x10 ⁻⁷	0.7	0.6x10 ⁻⁸	0.87
100	9x7μm	10 ²⁰	~ 1.2x10 ⁻⁷	5.7	0.35x10 ⁻⁸	0.88

4. Conclusions

The results show that the p-ZnO MSM Schottky photodetector, for an incident light of wavelength 280nm, has a total photocurrent of $\sim 1 \times 10^{-8}$ A. This is much higher than that of a p-ZnO Schottky diode ($\sim 3.9 \times 10^{-32}$ A at 4V) with a simple metal semiconductor junction. Hence we can conclude that p-doped ZnO is a photo-detecting material.

This performance can be further increased by using Au nanoparticles for plasmonic enhancement of photocurrent. It was observed that the plasmonic layer enhanced the output current of the MSM photodetector by a factor of 10. The values obtained in the simulation are close to the values quoted in the literature [13,14].

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