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ORIGINAL PAPER

Pressure Sensors Using Si/ZnO Heterojunction Diode

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Abstract

In nanoregime, heterojunction diodes have efficient applications in design and fabrication of sensors. Heterojunction diodes are formed by fusing two dissimilar semiconductors. Based on the combination of the materials used, these heterostructures find applications in bioelectronics and miniaturized sensors. In the literature, many different combinations are prevailing –GaN/AlGaN, Au/ZnO, NiO/ZnO. In this paper, a heterojunction diode is designed using Si/ ZnO combination and for the first time,the device is discovered to be used as pressure sensors.. The IV characteristics, energy band profile and CV curves of Si/ZnO is studied, analyzed and validated using TCAD-ATLAS software. This paper also proves that the performance of the device fits well for pressure sensing applications using COMSOL software.

Keywords Heterojunction diode · Biosensors

1 Introduction

In the recent years, the role of heterojunction diodes and heterostructures are multifold for designing biosensors. For forming heterostructures, wide bandgap materials are preferred than other materials. Because the wide band gap provides a pathway for energy transition in different forms which is used as photodetectors, UV sensors, etc. The sensing application depends on the material used in the heterostructures. The existing heterojunction diodes are constructed using thin film oxides such as ITO [1],ZnO [2], Al_2O_3 [4], Al:ZnO [5], or MgO [6].These oxides are laid down on the P-type substrates to reduce the undesired oxidation from the surface of the substrates. The existing substrates used as P-type materials are Si [7, 8], NiO [9], SiC [10], Diamond [11], CuO [12]. The heterojunction structures are classified into three types based on the energy bandgaps between the materials-Type I(Straddling),Type II(Staggered),Type III(Broken up). In the straddling type, the bandgap of one material is contained in the other (GaAs/AlGaAs). In the staggered type, the bandgaps overlap (InP/InSb) and in the broken up type of structure, the bandgaps do not overlap (GaSb/InAs). Based on the application, a specific type of heterojunction structure is designed.

The semiconducting materials used for designing heterojunction structures are MgO, ZnO, ITO,Al_2O_3 etc.. In this paper, Zinc Oxide is preferred and is used as N-type material for constructing the heterojunction diode. Zinc Oxide is a wide bandgap (3.3 eV) nanomaterial belonging to group II-IV.It finds a protruding place in the field of sensors for its overpowering characteristics like cheap cost, high binding energy, enhanced optical properties, high electron mobility, clear transparency, high chemical stability, high heat capacity, low thermal expansion and strong radiation hardness. It also exhibits n-type characteristics even before doping. The applications include bio-sensors, actuators, light-emitting diodes [13], photo detectors [14], solar cells [15, 16] pressure sensors and piezoelectric nanogenerators.

In the literature, ZnO based heterojunction diodes are being constructed and different characteristics are analyzed using fabrication. The optical property of ZnO is studied [7] using XRD (X-ray diffraction), AFM(Atomic force microscopy),

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SEM (Scanning electron microscope) fabrication techniques and the current voltage characteristics are analyzed in dark and light conditions. The structural properties of the ZnO thin films are investigated using X-ray photoelectron spectroscopy [17] and the enhancement of Raman peaks, near-band edge, intra-bandgap absorption has been observed on the ZnO thin films grown on AuNPs. ZnO heterojunctions are prepared using magnetron sputtering [18] and the ratio of ultra violet photocurrent to dark current. The fabrication works of ZnO based heterojunction diodes are carried out with many more techniques. Some of the existing heterojunction diodes are ZnO in combination with GaN, GaAs, Si, SiC and SrCu2O2 [19–21].

Eventhough many different deposition techniques are available to fabricate and show the experimental results of ZnO heterojunction diodes, performance of the device is not yet fully analyzed. This paper illustrates the design and study of ZnO based heterojunction diode. The I-V,C-V characteristics along with the energy band profile during ON and OFF states are analyzed and simulated using ATLAS simulation. The current voltage characteristics are also analyzed for various temperature and its dependence is more pronounced.. The electric field and potential characteristics are also simulated and its inferences are discussed. This paper also discusses the variation of displacement for different values of pressure which enables us to study the proposed combination of Si/ZnO heterojunction diode as a pressure sensor.

2 Device Structure

Figure 1 shows the schematic of the proposed Si/ZnO heterojunction diode with the dimensions. In general, Zinc Oxide exist as n-type in its natural form, and it involves many procedures to dope and convert in to p-type. In order to evacuate the potentials of Zinc Oxide and also considering the difficulty in converting it to p-type, many researchers have combined ZnO with some p-type semiconductor and this results in the formation of heterojunction diode. In the proposed structure, 250 nm of n type of Zinc oxide is deposited over 4750 nm of silicon substrate. The structure is bounded on either sides by 120 nm of Aluminium (Al) on the top and 120 nm of Silver (Ag) at the bottom. The silicon is chosen as the substrate in order to reduce the fabrication complexity and it is also available in abundant compared to other materials.. The structural combination helps in using the device in pressure sensing applications.

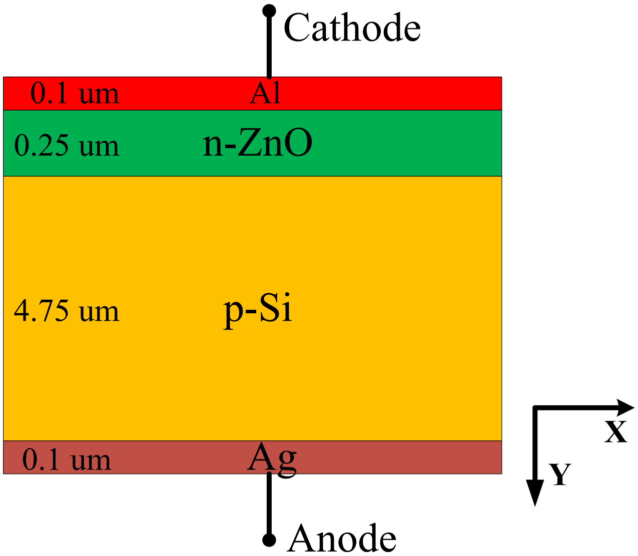


Fig. 1 Device Structure

3 Proposed Work

3.1 IV Characteristics

The structure of Si/ZnO heterojunction diode designed is shown in Fig. 1 b. Using the current transport mechanism of heterostructures [22, 23],the characteristic equation is derived [24] for Si/ZnO heterojunction diode as:

$$I = I_0\left[\exp\left(\frac{qV}{\eta kT}\right) - 1\right] \tag{1}$$

Where I_0 is the reverse saturation current, η is the ideality factor, k is the Boltzmann constant ($k = 1.38X10^{-23}$), q represents the charge and T is the temperature. The reverse saturation current is derived as.

$$I_0 = A_{contact} {}^{*} R_{constant} {}^{*} T^2 \exp\left(\frac{-q\phi_B}{kT}\right) \tag{2}$$

In this equation, $A_{contact}$ represents the effective contact area, $R_{constant}$ indicates the Richardson constant of ZnO, ϕ_B is the effective barrier height. The above diode equations are considered and the current is determined for various input voltages. The Si/ZnO heterojunction diode produces current in very small quantity and hence it is measured in log scale. The barrier height is based on the dimension of the device given by.

$$\phi_b = \frac{kT}{q}\ln\left(\frac{A_{contact} {}^{*} A_{contact} {}^{*} T^2}{I_0}\right) \tag{3}$$

The current voltage characteristics of the Si/ZnO is simulated using TCAD-ATLAS tool in Fig. 2. It is observed that the forward bias region attributes to the large surface state density near the bottom of the conduction band. The linear scale along the Y-axis shows the variation of current with varying voltages. The current is almost zero in the mid region

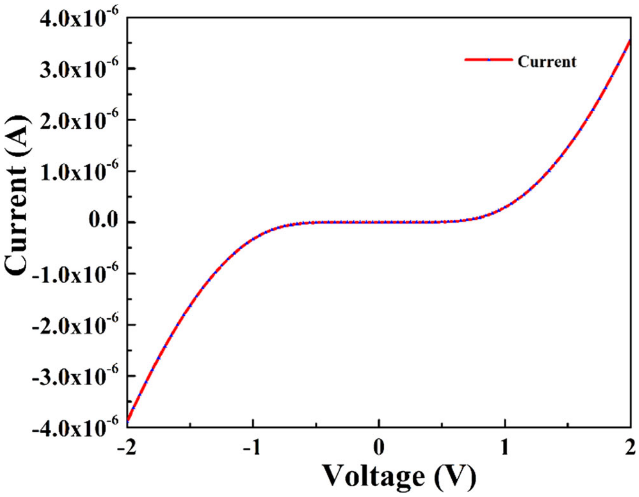
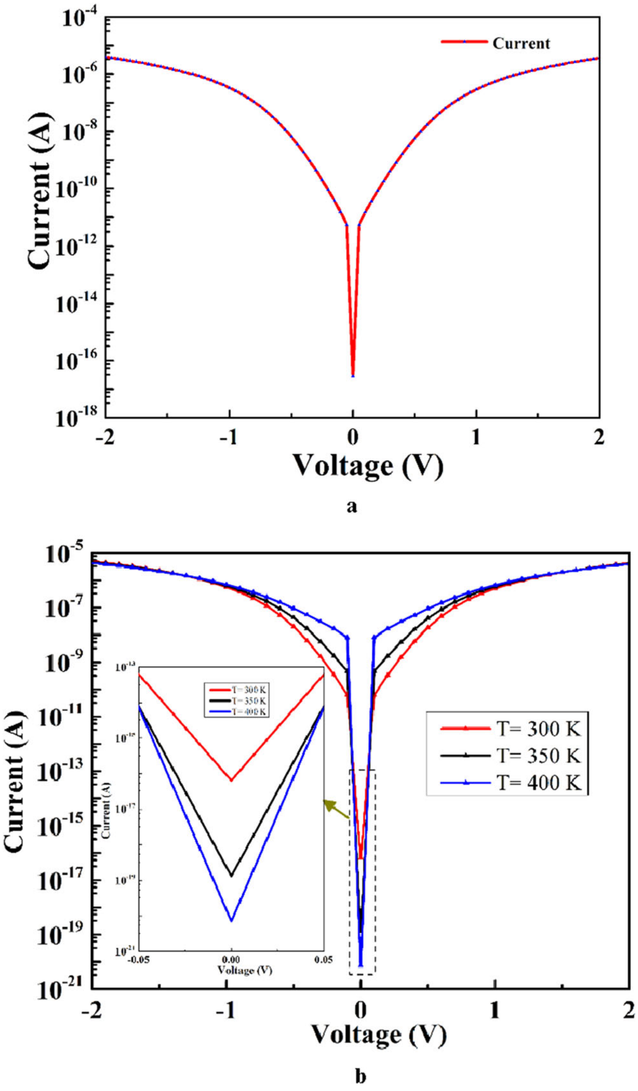


Fig. 2 IV Characteristics (along linear scale) of Si/ZnO Heterojunction diode

which reciprocates the expression of current using current transport mechanism.

The current is dependent on the temperature and it is given by the eq. (1). The IV characteristics are temperature dependent and the current increases when the temperature increases. Figure 3a shows the IV characteristics for T = 300 K. In this graph, the log scale is taken along the Y-axis which denotes the leakage current present in a very meagre amount when the voltage is zero along the X-axis. This infers that the current is due to minority charge carriers. In the Fig. 3b, it is observed that the reverse current increases with temperature. This is caused due to the thermally generated charge carriers which increase on increasing the temperature. In the homo junction diode, the reverse saturation current doubles for every 100C.Similarly in the proposed heterojunction diode, the Fig. 3b infers that the reverse saturation current increases by a scale of 10 for every 50 K.

From Fig. 4, it is inferred that the reverse current dominated by the carriers flowing through the low- barrier height. On increasing the reverse bias, there is a slight saturation in the reverse current. From the analytical eq. (2), it is observed that the square of the temperature is directly proportional to the reverse saturation current and this is proved showing that as the temperature increases the reverse saturation current becomes temperature dependent. It also compares IV curve of the proposed work with the existing experimentation work [1, 3] obtained by fabrication of ZnO based heterojunction device for different applications. The comparison shows that the proposed device characteristics coincides well with the fabrication results and hence it is validated.



a

b

Fig. 3 **a** IV Characteristics (along log scale) of Si/ZnO Heterojunction diode. **b** IV Characteristics (along log scale) of Si/ZnO Heterojunction diode for various temperature

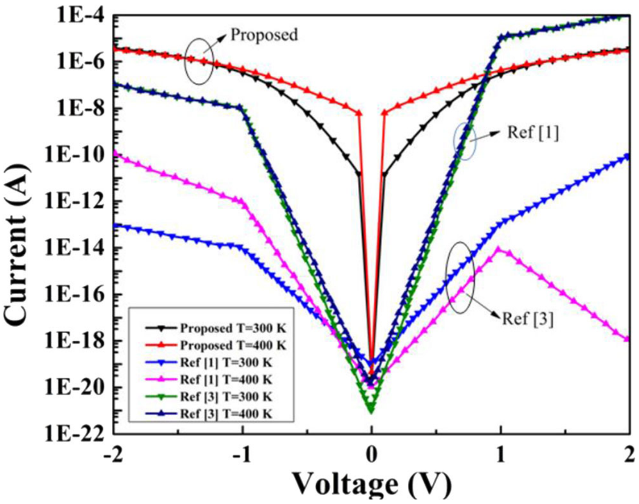


Fig. 4 IV characteristics of Si/ZnO heterojunction diode – Comparison with experimental work

3.2 C-V Characteristics

The Capacitance is analyzed [21–24] for the proposed heterojunction diode in order to investigate about the charge concentration of the device. The relation between the capacitance and the charge can be given as:

$$\frac{\left(A_{jn}\right)^2}{C^2} = \frac{2\left(V_{built-}V_{bias}\right)}{q\mathcal{E}_{ZnO}N_D} \tag{4}$$

Where A_{jn} represents the junction area, V_{built} represents built in potential, V_{bias} denotes biasing voltage, q represents charge,$\mathcal{E}_{ZnO}$ represents permittivity of ZnO and N_D represents donor concentration. The $\frac{(A_{jn})^2}{C^2}$ curve is calculated by inverting the C-V characteristics. The capacitance is directly proportional to the charge concentration of the device and it is observed for various voltages and the result is inferred in Fig. 5.The observation from the energy band diagram shows that the electron flow is alone responsible for the conduction of current and hence the capacitance characteristics is similar to PN abrupt heterojunction diode .

3.3 Energy Band Structure

The energy band structure of proposed Si/ZnO heterojunction diode is simulated using TCAD-ATLAS tool and is illustrated in Fig. 6. It infers the ON and OFF state of the conduction and valence band energy levels of the device. The movement of holes from silicon to Zinc oxide is less due to the larger value of valence band offset than the conduction band offset. This also proves that the current conduction is dominantly due to the flow of electrons from ZnO to Si of the heterojunction diode.

3.4 Electric Field

The electric field of the proposed device is analyzed through cut lines and X-Y axis available in TCAD-ATLAS tool. The electric field of the heterojunction diode reaches maximum value of $8.0X10^3$ and it is obtained due to the heterojunction formed by ZnO and Silicon (Fig. 7). The electric field peak is in the ZnO part and in the initial stage of silicon ie. in the heterojunction. This is due to the recombination of electrons at the center of the device.

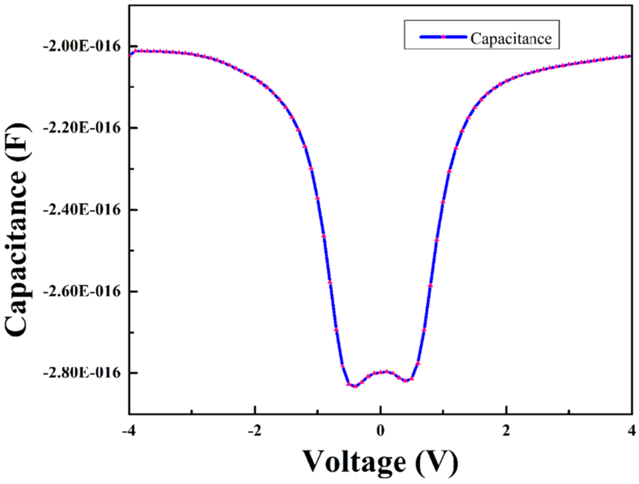


Fig. 5 CV characteristics of Si/ZnO heterojunction diode

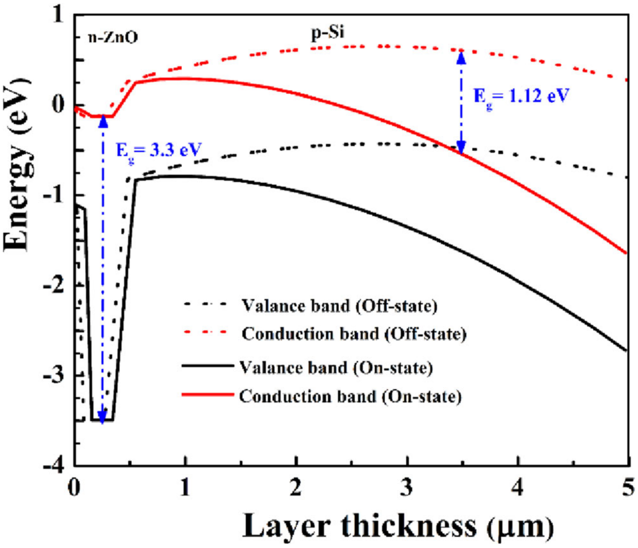


Fig. 6 Energy band diagram of Si/ZnO heterojunction diode

3.5 Potential

The potential distribution of the proposed diode is shown in Fig. 8. The curve shows that the potential is slightly higher in the ZnO, then the curve decreases slowly and the potential starts increasing gradually. This is because of the bandgap difference between the two materials. The maximum potential is 0.5 V in the ZnO layer and 2.4 V in the Silicon layer.

3.6 Recombination Rate

The recombination rate of the proposed heterojunction diode is simulated using ATLAS and it is illustrated in Fig. 9.The

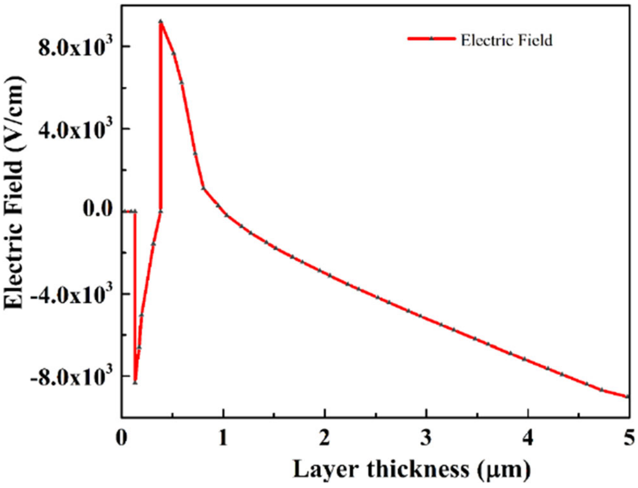


Fig. 7 Electric field of Si/ZnO heterojunction diode

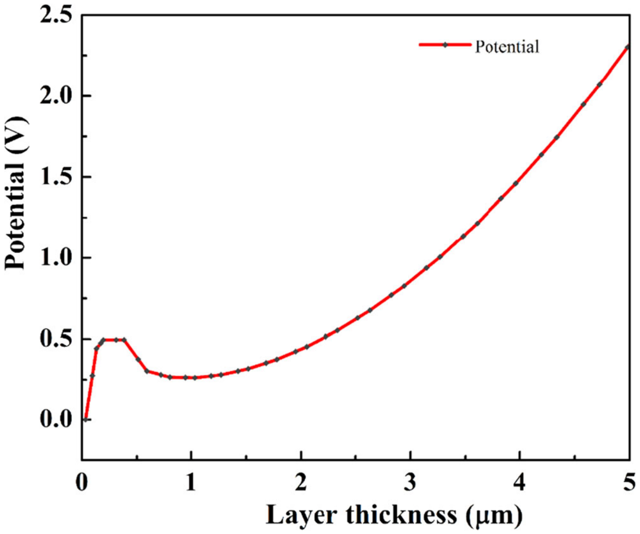


Fig. 8 Potential Distribution of Si/ZnO heterojunction diode

recombination rate has a higher value in the silicon layer compared to the ZnO layer. The electrons from the ZnO flow

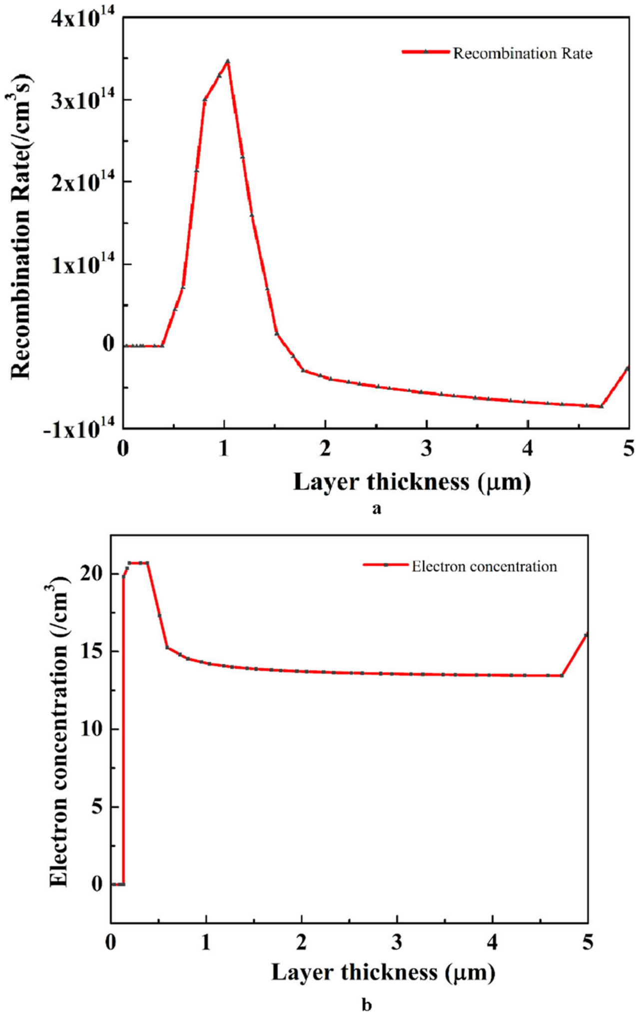


Fig. 9 **a** Recombination Rate of Si/ZnO heterojunction diode. **b** Electron Concentration of Si/ZnO heterojunction diode

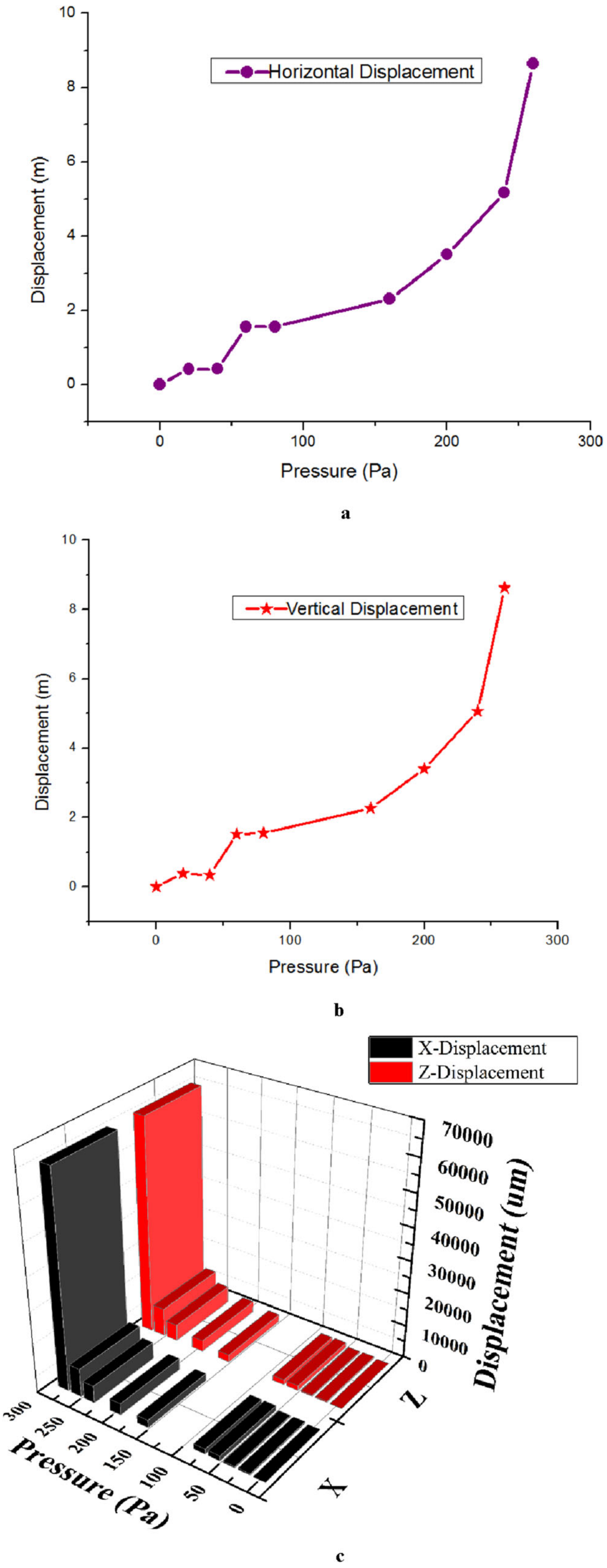


Fig. 10 **a** Horizontal displacement of Si/ZnO heterojunction diode for different values of pressure. **b** Vertical displacement of Si/ZnO heterojunction diode for different values of pressure. **c** Displacement of Si/ZnO heterojunction diode (both in horizontal and vertical direction) for different values of pressure

through the heterojunction to the silicon layer and maximum recombination occurs at that instant. The maximum value of the recombination rate is 3e14.The electron concentration is shown in Fig. 9b proves that the higher recombination occurs at the heterojunction near the silicon layer.

4 Application as Pressure Sensor

The characteristics study of Si/ZnO heterojunction diode infers that the device can be used for pressure sensing. Since it is difficult to analyze the pressure sensing characteristics using TCAD, a physics based tool, COMSOL is used. Different ranges of pressure is applied to the device and its displacement is analyzed both in horizontal and vertical directions. The pressure input ranges from 0 to 300 Pascals. The pressure is applied on the top of the Si/ZnO heterojunction diode and it produces displacement both in horizontal (X) and vertical (Z) direction. The displacement of the device increases in both the directions in a micro metre range when the pressure is increased. This is shown in the Fig. 10a,b, c.The increase in the curve and the limits of the displacement makes the device suitable for touch sensor applications.

5 Conclusion

In this paper, the Si/ZnO heterojunction diode is designed and its performance is analyzed. The IV, CV characteristics,energy band diagram, electric field, potential and recombination rate of the designed device are simulated using TCAD-ATLAS tool. The experimental results are extracted from the literature and the proposed model is also compared for different values of temperature. The pressure sensing characteristics are analyzed using COMSOL software. The device is also driven by various pressure inputs and the displacement is observed for both vertical and horizontal direction. This makes the device fit well for pressure sensing applications.

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Data Availability Data can be shared upon request.

Declarations

Ethical Approval The authors declare that all procedures followed were in accordance with the ethical standards.

Consent to Participate All the authors declare their consent to participate in this research article.

Consent for Publication All the authors declare their consent to participate in this research article.

Conflict of Interest There is no conflict of interest in this work.

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