

Polyaniline Based Field Effect Transistor For Humidity Sensor

Mandira Biswas (✉ mbiiswas@gmail.com)

Jadavpur University Faculty of Engineering and Technology <https://orcid.org/0000-0001-5420-5923>

Anup Dey

Jadavpur University Faculty of Engineering and Technology

Subir Kumar Sarkar

Jadavpur University Faculty of Engineering and Technology

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Abstract

In this present research work, we presented a new Bottom Gate P-Type Organic Field Effect Transistor (OFET) humidity sensor and its applicability towards humidity has been experimentally demonstrated. P-type organic semiconductor polyaniline (PANI) has been used in a variety of applications, including logic circuit components, electromagnetic shielding, chemical sensing, and anticorrosion. Humidity sensor can be used to monitor relative humidity (RH) in various environments. We only focus on the fabrication of conducting polymer OFETs with top contact to measure humidity and verify I-V properties. The current saturation (I_{sat}) of p-type OFETs was $0.8 \mu\text{A}$, while the threshold voltage V_{Th} was 2.2V . The results of FESEM have been performed to confirm that deposited thin film grown on the substrate is purely uniform. The Proposed sensor shows that organic gate dielectrics are a low-cost alternative to inorganic gate dielectrics with good electrical performance. The proposed OFET-based sensors have a number of benefits, such as high sensitivity, low cost, quick response, and physical flexibility.

I. Introduction

Sensor technology has been used in advanced applications, resulting in low power, miniaturized, high-speed, and cost-effective systems. Organic electronics is becoming a prominent topic in the fields of displays, sensor arrays, and photovoltaics, among other things. OFETs provided high-quality components for active matrix displays, radio frequency identification tags, and a variety of other small-scale integrated systems. This will allow for the low-cost and low-temperature fabrication of mechanically flexible electronics on flexible substrates. Conducting polymers (CPs) are organic compounds with π -orbital systems that allow electrons to travel from one end of the polymer to the other. Because of its mechanical flexibility, ease of synthesis and high electrical conductivity, conducting polymer (CP) is used. At room temperature, CPs can help sensors to improve their speed, sensitivity, and short response time. Polyaniline (PANI), Polypyrrole (PPy), Poly(phenyl vinylene) (PPV), Poly(3,4-ethylene-dioxythiophene), and PEDOT are only a few of the organic conducting polymers available. PANI, a p-type organic semiconductor material with good electrical conductivity and stability, is one of these organic compounds. Because of its ease of synthesis, room temperature operation, and relative stability, polyaniline (PANI) has been used for a variety of applications including logic circuit components, electromagnetic shielding, chemical sensing, and anticorrosion. This device can be used in low-power applications (Ref 1-4). Humidity sensors can be used to measure relative humidity (RH) in a variety of weather. PANI has been used in humidity sensor devices based on the electrical conductivity with water vapor. Polymers are the most common type of material used to fabricate the humidity sensors. Humidity is an important environmental characteristic that can be used for a variety of applications including instrumentation, automated systems, agriculture, and climatology. Plantation protection and soil moisture monitoring are two applications of humidity sensors in agriculture. To get high performance of humidity, sensing materials must have high surface to volume ratio to interact with the water molecules repeatedly for longer life cycle and faster response (Ref 5-6).

In this paper, we propose a bottom gate OFET device composed of PANI as a conducting channel and SiO₂ act as an insulator on n-type silicon substrate, which will be used as a humidity sensor based on organic field-effect transistor (OFET). This device is compatible with low power applications. In this work, we only concentrate on fabrication of conducting polymer OFET with top contact to evaluate the humidity and verify I-V characteristics. The current saturation (I_{Sat}) of p-type OFETs was 0.8 μA, while the threshold voltage V_{Th} was 2.2V. The FESEM (Field Emission Scanning Electron Microscopy) have been presented. The Proposed sensor shows that organic gate dielectrics are a low-cost alternative to inorganic gate dielectrics with good electrical performance.

ii. Device Structure And Operation

The cross section of our proposed device, Bottom Gate OFET (BGOFET) is illustrated in Figure: 1 in which organic polymer PANI act as an active conducting layer. In the bottom gate structure, the electrodes can be deposited after the PANI coating. Here organic semiconductor is p-type PANI conducting polymer. Metal (Al) is deposited on source, drain and gate region as electrode (Ref 7-10). N-type heavily doped silicon is placed between gate electrode and oxide layer, thickness of this silicon layer 0.5mm and oxide thickness is 2 nm. The insulator can be made from a variety of dielectric materials, even though SiO₂ is a common choice. A voltage is applied to the gate metal to control the amount of current flow from drain to source region. In our proposed OFET, the relatively high hole mobility p-type channel is used. A much higher negative voltage causes a p-type channel to form at the semiconductor-insulator interface. A drain to source negative voltage (V_{DS}) causing holes to flow from the source to the drain and hence a negative current started from the drain to the source (I_{DS}). As the magnitude of the drain-source voltage (V_{DS}) is increased, I_{DS} is enhanced until "pinch-off," at which point the p-channel pinches closed on one side and the drain current saturates at its maximum value (Ref 11-12).

We know,

$$g_m = \left. \frac{dI_d}{dV_{gs}} \right|_{V_{ds}=const} \dots\dots\dots(1)$$

$$g_d = \left. \frac{dI_d}{dV_{ds}} \right|_{V_{gs}=const} \dots\dots\dots(2)$$

iii. Experimental Details

A. Materials and Instruments

Polyaniline (PANI) was purchased from Sigma-Aldrich which was in liquid form (product number 650013). The substrates used are commercially available. The thickness of silicon layer is 0.5 mm with resistivity 10-1Ωcm; the thickness of the oxide layer on the Si is 0.5 μm. It is highly Phosphorus-doped Si in (100) orientation. KEITHLEY 2635A system source was used to measure current-voltage characteristics of OFET. Scanning Electron Microscope (FESEM) was used to confirm that deposited thin film grown on the substrate is purely uniform and does not have any other scattered crystals on the thin layer of PANI. The properties of polyaniline in liquid form are enlisted below:

TABLE: Liquid form of PANI Specification

| Concentration | Particle size | Conductivity | Viscosity | Boiling point | Density |
|--------------------|---------------|--------------|--------------|---------------|----------------------|
| 2-5 wt % in xylene | <400 nm | 10-20 S/cm | ~3 CP (lit.) | 116°C | 0.9-0.95g/mL at 25°C |

B. Synthesis of Polyaniline

Polyaniline(PANI) solution was prepared using Solgel method. Polyaniline was dissolved in 10ml N,N-Dimethylformamide (DMF). Then, the mixture is stirred properly up to 1hrs. The colour of the solution is green.

IV. Fabrication Of Ofet

A. Cleaning the Substrate and Oxidation of Wafers

At first, an n-type Silicon substrate was taken with dimension of 1.5 cm × 2.5 cm and cleaned with acetone for 10mins. The substrates were rinsed with deionized (DI) water for 5mins in an ultrasonic cleaner for cleaning purpose. To remove the acidic organic compounds, the wafers are cleaned using H₂O:H₂O₂:NH₄OH 5:1:1 at 76°C for 10 minutes and then pass it into cold water (Ref 16-18). To remove the organic compounds, the concentration of the sulfuric acid (H₂SO₄) and hydrogen peroxide (H₂O₂) are used with 1:1 ratio followed by a rinse using deionized (DI) water. The next step is Alkaline Organic compound. The concentration of the H₂O, H₂O₂, and HCL are used with ratio of 6:1:1 and heat at 700C for 10 minutes and then clean in de- ionized water. The last step is the sample is dipped in 10% HF for 3 to 4 minutes. The cleaned substrates were rinse and dry in a vacuum oven for at least 30 min before use. This clean process takes approximately 30 mins. After the clean step the wafers should be loaded immediately in the quartz boat for the oxidation step. This insulator was grown on silicon wafer using wet oxidation and it took 30 minutes at 1000°C in a horizontal furnace. In nitrogen, the furnace is set for a 10 minutes temperature ramp-up. In the case of the wet oxidation after temperature ramp-up the water valve of the furnace should be open and it took 1hours and then again dry oxidation for 30mins.

B. Polyaniline Deposition Using Synthesis Process

Before depositing the semiconductor layer, sample are cleaned with 2-propanol and then the sample were taken out of the solution and dry in a vacuum oven for 2 min. PANI solutions were deposited on dielectric layer i.e. SiO₂ by using spin coating at 4000 rpm for 40 sec. The channel length is 100 μm and channel width is 2 mm.

C. Electrode Formation

After the PANI deposition, source and drain electrodes were deposited by Al with thickness of 150 nm over the PANI layer using the thermal evaporation method under a pressure of 4×10^{-6} mbar. In the same method, the gate electrode (Al) was thermally evaporated on Si wafer. Then, inside the Ag paste, three copper wires were placed one by one and heated at 150⁰C for 15 min.

The copper leads are taken for connection to perform the characteristic measurements of OTFT through the multimeter. I-V characteristic of the OFET was measured at different gate voltages (V_g) applied with DC power supply between source and gate in different humidity levels range of 65% RH.

V. Result And Discussions

The Figure 5(a) illustrates the drain current I_D vs drain voltage V_D curve of a p-channel OFET at different gate voltage in various atmospheric environment. The active channel's I_D increases with proportion to the negative gate voltage (V_g). The saturation current (I_{Sat}) is determined to be 0.8 μA, while the threshold voltage V_{Th} is 2.2V at $V_{gs} = -1V$. When higher gate voltage ($-V_G$) is applied, then current flows from source to drain electrodes via holes. The I_{DS} are linear with $-V_{DS}$ under this circumstance, corresponding to the linear region. The transfer characteristic curves of the OFET device generated by dual changing the gate voltage for $V_{DS} = -2V$ and $-5V$ are shown in Figure 5(b). The space charge region under the channel and near the drain region becomes widens as the $-V_{DS}$ increases, finally reaching a pinch-off point condition where the channel width is zero. The I_{on}/I_{off} ratio, transconductance (g_m), and conductance (g_d) are calculated from these curves to be 10^4 , $13.7 \times 10^{-4} \text{ } \bar{\cup}$ and $10^{-6} \text{ } \bar{\cup}$ respectively.

Figure 6 is an FESEM image displaying the cross-section image of PANI/ SiO₂ thin film on silicon substrate at room temperature. The surface of the thin-film of PANI has grain sizes of few nanometers with an average scale size of 1 μm. FESEM image confirms that deposited thin film grown on the substrate is purely uniform and does not have any other scattered crystals on the thin layer of PANI.

Figure 7. shows that resistance of PANI increases in the region A-B and then decreases with the increase of the temperature in the region B-C. The mobility of the dopant ion, which is weakly connected to the polymer chain by weak van Waals forces. This can be assigned that for low resistance or high in

conductivity, the humidity is high. The equation of relative response of the sensor i.e., Relative Humidity (RH):

$$RH (\%) = [(R_a - R_v) / R_a] \times 100$$

where R_a represents the resistance in air and R_v represents the resistance in vapor in different temperature [Ref 11].

Figure 8 shows that the PANI based OFET gives better performance at higher RH%. It is seen that as relative response (relative humidity) is increased from 45% to 65%, response is improved significantly. But beyond that limit relative response is degraded continuously. Temperature decreased when relative humidity is high. However, relative humidity is inversely proportional to temperature as air warms it can hold more moisture so that the percentage of potential humidity decreases.

Figure 9(a) shows the drain current shows increasing tendency with the increase of relative humidity up to 65%. However, beyond that limit drain current drastically reduces with increase of relative humidity as evident from figure 9(a). Figure 9(b) shows the variation of threshold with the change of the values of 45-65 RH%. This figure also supports the results of Figure 9 (a) reflecting that their fabricated OFET is best usable in the range of RH%. Further, it has been observed that the fabricated device shows good reversibility with increase and decrease in humidity.

V. Conclusion

In conclusion, it can be mentioned that we have fabricated a PANI/SiO₂ based OFET for using it as a humidity sensor. We have investigated the I_D - V_{GS} , I_D - V_{DS} characteristics of the fabricated OFET. In state of varying humidity, we have varied temperature of the system (as relative humidity is inversely proportional to temperature because it has air warmers it can hold moisture). We have also measured relative response also called relative humidity with change of temperature. Hence we have studied the performance of the fabricated OFET as a humidity sensor with I_d vs relative humidity in fig 9(a) and V_{th} vs. relative humidity in fig 9(b). It has been observed that the fabricated OFET shows better response in the RH% range of 45 to 65. Further, the stability of current OFET act as humidity sensor has also investigated and found superior compared to other humidity sensor.

Declarations

1. Ethics approval and consent to participate

Not applicable.

2. Consent for publication

Not applicable.

3. Availability of data and material

Data is available and material also available to support the result.

4. Competing interests

The authors declare that they have no competing interests.

5. Funding

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6. Authors' contributions

Professor Subir kumar Sarkar analyzed data after taking humidity sensor data and guided us to complete the whole work. Anup Das helps in oxidation process. Mandira Biswas has a major contribution in writing the manuscript and after getting the data to plot the figure. All authors read and approved the final manuscript.

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Figures

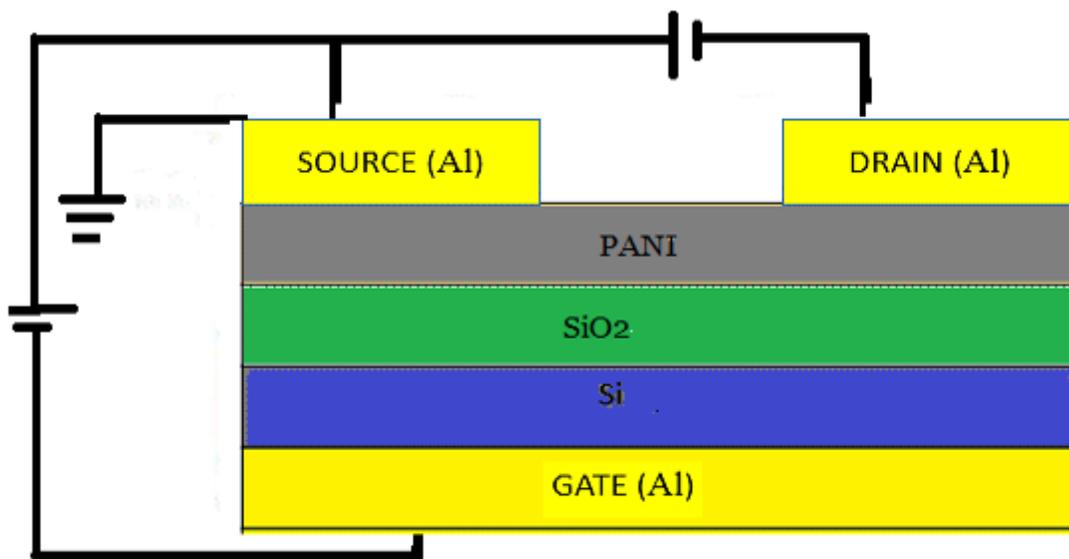


Figure 1

PANI based Organic Field Effect Transistor structure.

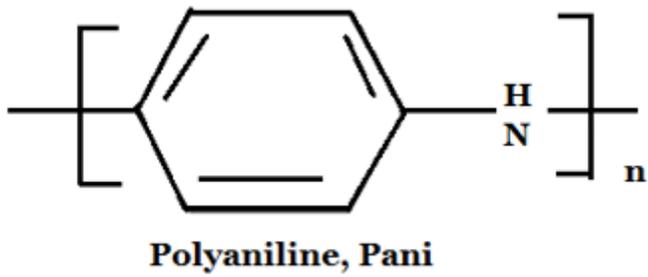


Figure 2

Structure of PANI

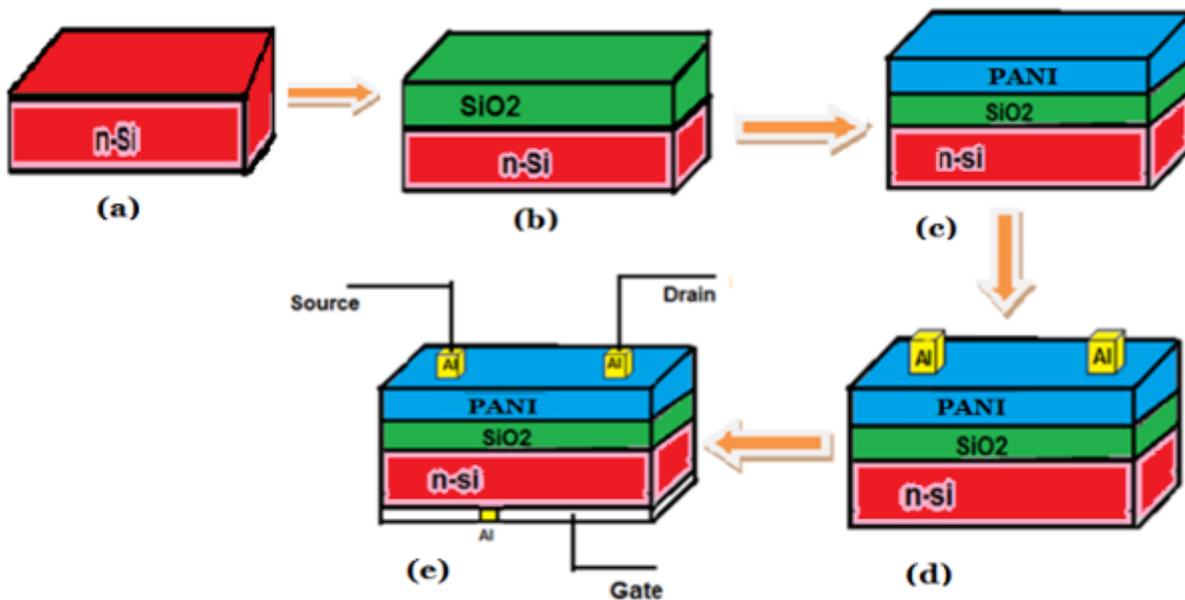


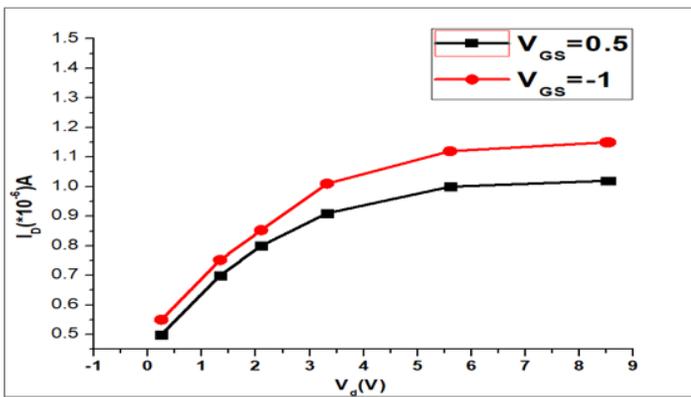
Figure 3

Polyaniline (PANI) based Field Effect Transistor fabrication steps: (a) Cleaning the n-type Si substrate. (b) Oxidation of wafer (c) PANI deposition using Synthesis process. (d) Electrode formation of source and drain contact (e) evaporation of gate metal

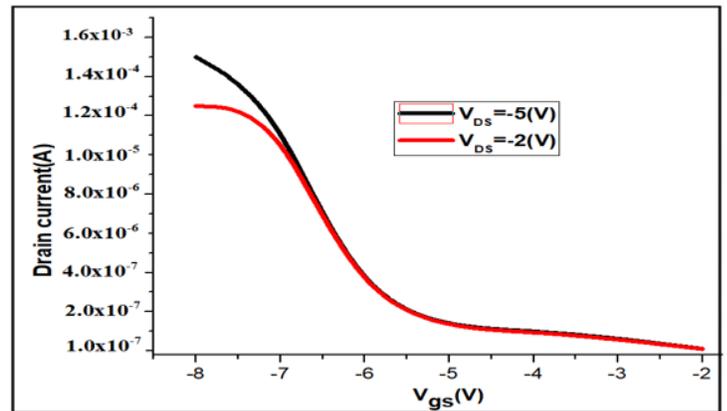


Figure 4

Measurement of Humidity using fabricated device



(a)



(b)

Figure 5

(a) I_D vs. V_{DS} graph as a function of V_{GS} . (b) Transfer characteristic curves of OFET device obtained by dual varying of the gate voltages.

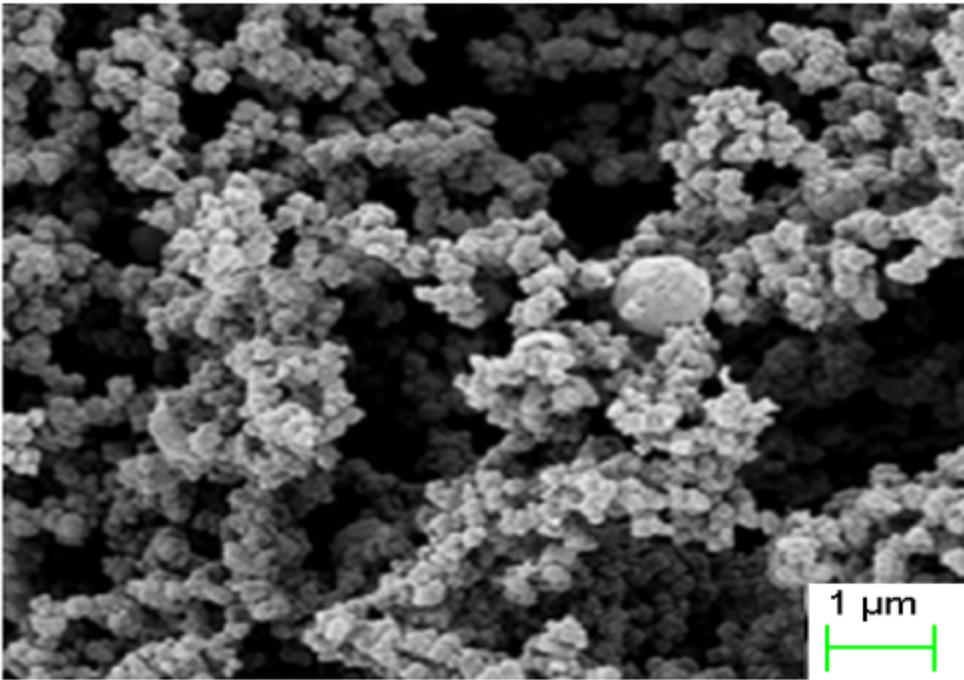


Figure 6

FESEM image of PANI based OFET sensor.

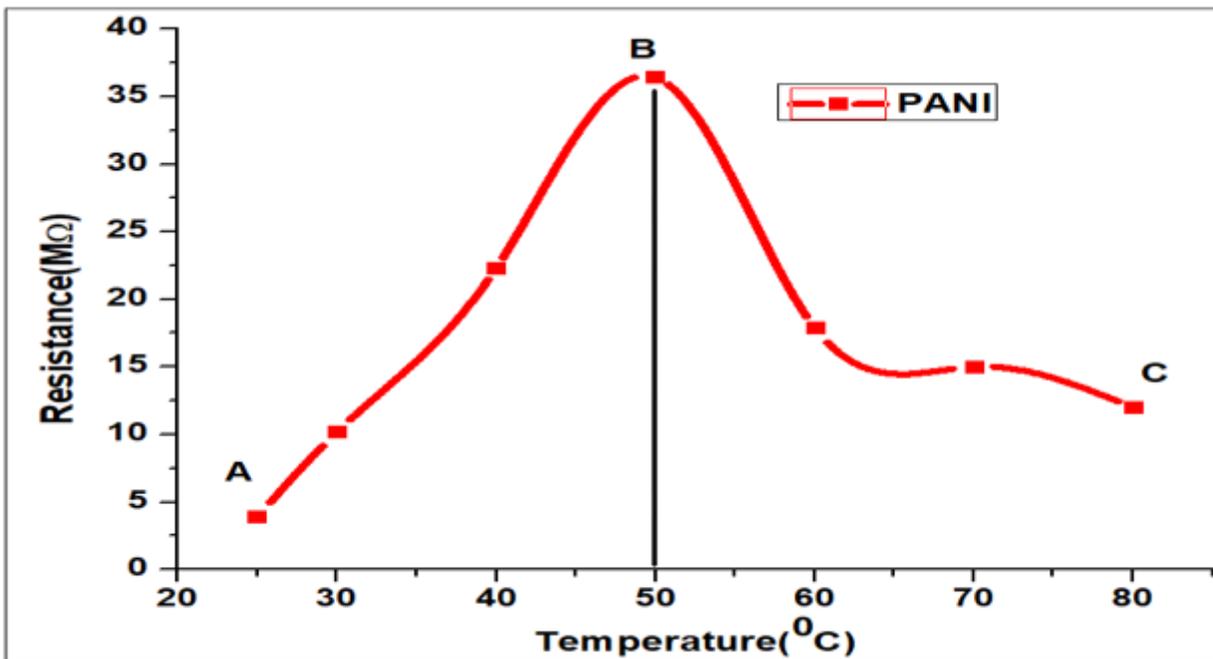


Figure 7

Resistance vs temperature graph

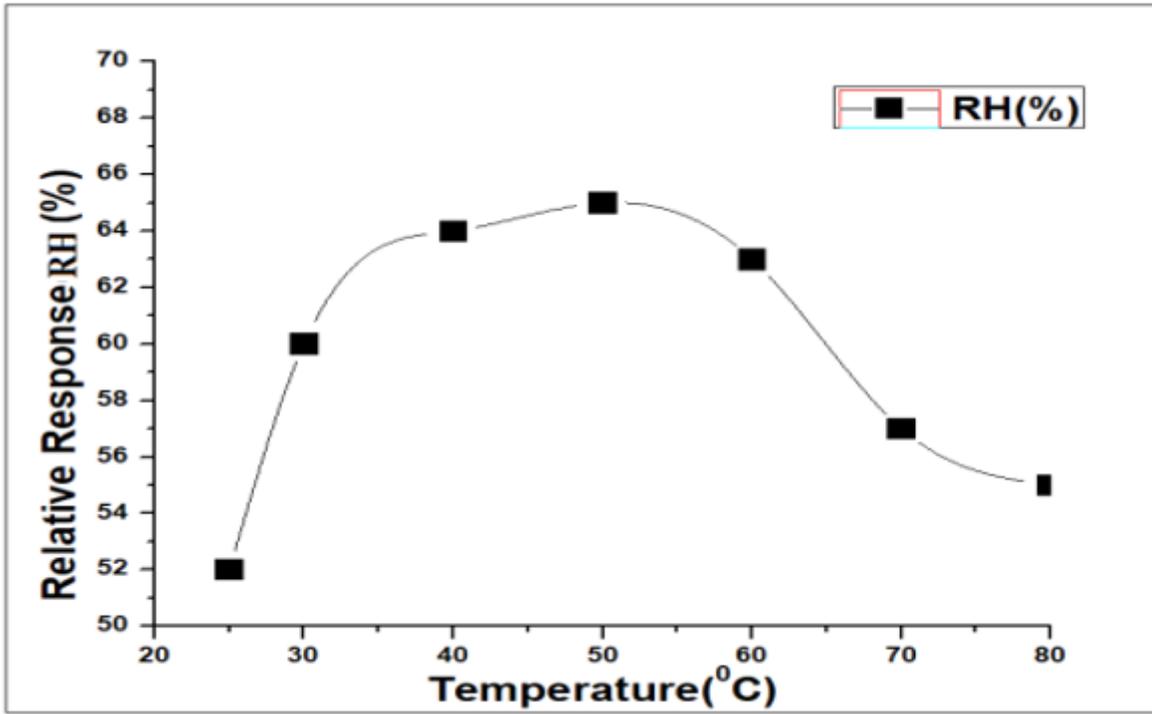
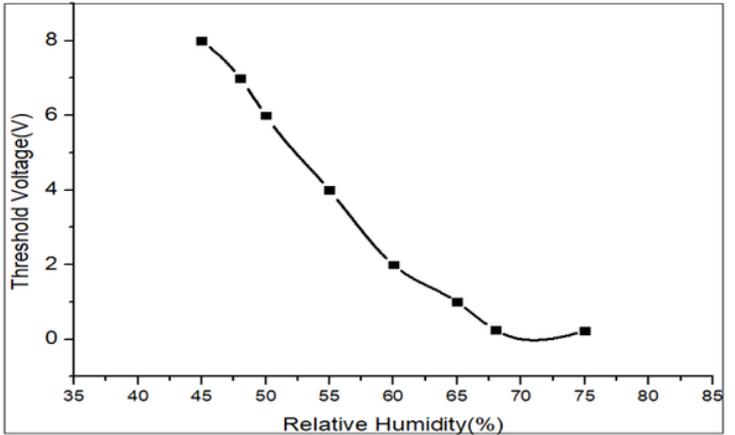
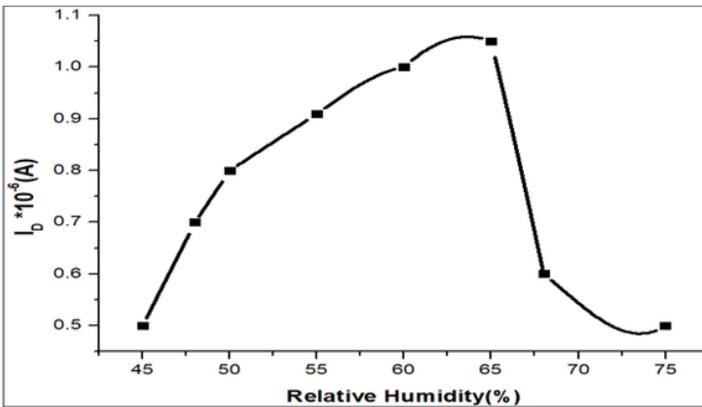


Figure 8

Relative humidity Vs temperature



(a)

(b)

Figure 9

(a) Drain current versus relative humidity plot and (b) Threshold voltage versus relative humidity plot at $V_{DS} = 8V$.