Introduction

Over the past few decades, metal oxide semiconductors have received great deal of attention due to its high sensitivity, stability, and relatively low cost. However, there are still some drawbacks in semiconductor metal oxide-based sensor such as selectivity and high operating temperature. These drawbacks led to the development of new alternative one-dimensional (1D) and two-dimensional (2D) nanomaterials as a perspective sensor material such as pristine semiconducting and metal oxide semiconducting materials, graphene, and transition metal dichalcogenide. Recently, 1D and 2D nanomaterials have attracted tremendous attention in nanoelectronics device due to its outstanding performance, stability and which works at room temperature. The 2D layered material such as MoS$_2$, MoSe$_2$, WS$_2$, WSe$_2$, GaS, GaSe, and Black Phosphorous have a great role in nanoelectronics and optoelectronics device due to high surface to volume ratio, semiconducting nature, and tunable and wide bandgap.

The bulk Tellurium (Te) is a well known $p$-type semiconducting material having narrow band gap (0.32 eV) and it possesses many interesting properties such as photoconductivity, high piezoelectricity, thermoelectricity, sensor, and optical properties. The Te nanostructure morphology of various semiconducting materials such as nanorod, nanotubes, nanobelts, and nanowires are potential candidates for many applications in divers’ field. So far superior field emitter, photodetector, field effect transistor, and gas sensor made from various well-aligned Te nanomaterials have been reported. The synthesis of Te nanowire is very well known in the literature via poly vinyl pyrolidone (PVP) as reducing agent as it reduces the tellurium oxide in to elemental tellurium in a nanoform.

Hydrogen peroxide ($\text{H}_2\text{O}_2$) is well known for hammering of biological systems and it involves in the neuropathology and central nervous system’s diseases. In addition, $\text{H}_2\text{O}_2$ can also cause the acid rain so it may be harmful to environment too. Therefore, $\text{H}_2\text{O}_2$ sensing investigation is very important in clinical research and environmental applications. The $\text{H}_2\text{O}_2$ can be detected by various methods such as chemiluminescence, fluorimetry, fiber optics device, chromatography, and various chemical methods. The $\text{H}_2\text{O}_2$ plays a very important role in our body.

Abstract

Tellurium (Te) nanowires were synthesized using hydrothermal method. The as-synthesized Te nanowires were characterized using various techniques such as SEM, TEM, X-RD, and Raman spectroscopy. The X-RD and Raman results confirm the compositional and phase formation of the Te nanowires. The SEM and TEM results reveal the nanowires with length ~25 μm and diameter ~500 nm. The sensor devices were fabricated based on Te nanowires, which show good and stable response to humidity and $\text{H}_2\text{O}_2$. The humidity sensing result shows the Te nanowires-based sensor device exhibits good response and recovery time of ~54 and 65 s.

Keywords

Tellurium nanowire, Humidity sensor, $\text{H}_2\text{O}_2$ sensor

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important role in the food control, pharmaceutical, clinical areas, and chemical industries. In addition, H_{2}O_{2} is also used in industrial applications.\textsuperscript{42}

We report in this article the synthesis of Te nanowires using simple hydrothermal method and with PVP as surfactant and stabilizer, which gives the 1D nanowire structure of Te. Further, humidity sensing was carried on the Te nanowire-based device which shows the good sensitivity, very fast response, and recovery time at room temperature as compared to the other materials GO, Fe_{2}O_{3}, TeO\textsubscript{2}, and other 1D and 2D nanomaterials.

**Experimental section**

**Synthesis of Te nanowire**

All the chemicals used for the synthesis were purchased from Sigma–Aldrich and used as it is without any further purification. In the typical synthesis process, 0.5 g-TeO_{2} and 0.5 g-PVP were added into the 30 ml-deionized water under constant stirring at a room temperature. The obtained suspension was added into the 50 ml Teflon-line stainless steel autoclave. The autoclave kept in oven at fixed 180 °C for 48 h and after cooling to room temperature, gray color precipitate was obtained. The obtained precipitate was then washed several times with distilled water followed by centrifugation and washing several times with ethanol. The precipitate was kept in vacuum oven for 8 h at 70 °C for drying.

**Characterizations**

**Raman spectroscopy**

The Raman spectra were recorded at room temperature, with a (LabRAM HR) using Ar laser (514.5 nm) in the back scattering geometry with laser power ~1 mW.

**Device fabrication and sensing performance**

**Device fabrication for humidity sensor**

Highly conducting indium doped tin oxide (ITO)-coated glass substrate was used for the humidity sensor device fabrication. The channel length of ~300 μm and channel width ~1 cm was fabricated. After that thick film of Te nanowire sample was drop casted into the channel.

**Humidity test**

For the humidity sensing measurement, the saturated salt solutions were prepared as per procedure reported earlier.\textsuperscript{6,25,43}

**Electrical characterization**

The electrical measurements of the humidity sensor device was measured using Keithley 2612, a system source meter which was connected to a computer through GPIB 488A interface cable.

| Sr. No | Name of nanomaterial      | Response time (sec) | Recovery time (sec) | References |
|--------|---------------------------|--------------------|--------------------|------------|
| 1      | Graphene oxide film       | 0.03               | 0.03               | 45         |
| 2      | Black phosphorus nanosheets | 101                | 26                 | 43         |
| 3      | V_{2}O_{5} nanosheets     | 240                | 300                | 6          |
| 4      | Fe_{2}O_{3} nanoparticle  | 29                 | 630                | 46         |
| 5      | SnO_{2} nanowires         | 120–170            | 20–60              | 47         |
| 6      | Te nanowires              | 54                 | 65                 | Present work |

Figure 1  The schematic of a proposed mechanism of Te nanowires synthesis

Table 1  The comparative humidity sensing behavior of various nanomaterials
All electrochemical measurements were carried out with the help of a BioLogic potentiostat. Te nanowire was dispersed in ethanol with concentration of 0.25 mg/ml and sonicated for 30 min. Then, 100 μl of that solution was drop casted on ITO glass with area (1 × 1) cm². The conventional three-electrode system was used with a Te nanowire on ITO as a working electrode, a Pt wire as counter electrode, and a saturated calomel electrode as reference electrode. All voltammetric and amperometric measurements were carried out in phosphate buffer pH 7.4.

**Results and discussion**

Figure 1 shows the typical schematic diagram of proposed reaction mechanism. In the typical synthesis process, PVP gets absorbed on the surface of TeO₂ and which act as a reducing agent. Then the TeO₂ gets reduced and the formation of Te nanowire takes place. During the formation of Te nanowire, PVP molecule promotes the agglomeration of nanoparticle and leads to formation of 1D nanowires. The synthesis of Te nanowires is a very easy one-step process and it gives the ~95% product yield.

Figure 2a shows the typical Raman spectra of as synthesized Te NWs and no other characteristic peaks were observed. It shows the presence of two peaks at about 119 and 140 cm⁻¹ at room temperature. These two peaks are due to the A₁ bond bending and A₁ bond stretching mode or E mode. These symmetric, sharp, and broad band show the highly crystalline and purity of Te nanowire. Figure 2b shows the X-ray diffraction pattern of as-obtained Te nanowires. All the peaks that
Figure 4 Hydrothermally synthesized Te nanowire a, b low resolution TEM images, c high resolution TEM image, and d corresponding SAED pattern showing highly crystalline nature of Te nanowires.

Figure 5 Hydrothermally synthesized Te nanowire a typical I–V curves at various RH, b the typical Resistance vs. relative humidity plot, c Sensitivity vs. RH plot, and d typical I–t plot for switching RH between 97 and 11%. Inset of Fig. c shows the schematic of two-probe sensor device.
are present in the diffraction pattern clearly indicate the highly crystalline hexagonal phase of Te nanowire having the lattice constant $a = 0.4502$ nm and $c = 0.5920$ nm, which matches well with the standard JCPDS data card No. 36-1452. The high intense peak at (110) plane clearly indicates the preferential growth of Te nanowire along with the [001] direction due to the surface free energy difference. The sharp and narrow peak shows high purity and good crystalline quality of Te nanowires.

Figure 3a, b shows the low-resolution SEM images and Fig. 3c, d shows the high-resolution images. It shows the uniform nature of nanowires with average length ~25 μm and diameter ~500 nm, respectively. Figure 4a, b shows low-resolution TEM images of the as-synthesized Te nanowire. Figure 4c shows the typical high-resolution transmission electron microscopy image of the Te nanowire, it exhibits the well-resolved lattice fringes, indicating the highly crystalline nature of Te nanowire. Figure 4d shows the typical selected area electron diffraction (SAED) pattern, showing highly crystalline nature of Te nanowire.

The humidity sensing performance of Te nanowire is also investigated at a room temperature and pressure. In present investigation, we have prepared the sensor device from as-synthesized Te nanowire and tested at room temperature. Figure 5 shows the humidity sensing performance of as-prepared Te nanowire material-based sensor device. Figure 5a shows the typical Current vs. Voltage (I–V) plot carried out at a different relative humidity (RH) and the nature of the graph showed the obvious increase in resistance with increase in RH from 11% to 97%. The resistance increases with increasing RH level which means that the conductivity decreases with respect to increasing RH level which is depicted in the Fig. 5c. The typical schematic of two-probe sensor device is shown in inset of Fig. 5c. The sensitivity as a function of relative humidity plot is shown in the Fig. 5c. The sensitivity is calculated using the formula:

$S = \frac{(R_{97} - R_{\Delta RH})}{R_{\Delta RH}}$

where $R_s$ is resistance of the sensor device at 97% RH and $R_{\Delta RH}$ is the change in relative humidity at various RH levels. When the sensor device was exposed to lower humidity (11%), it showed the maximum sensitivity ~244%. Figure 5d shows the typical Current vs. time (I–t) plot. In this case, water molecule acts as electron acceptor so resistance increases with increase in RH which results in p-type doping. The sensor device was switched between RH 97% and RH 11% to calculate the typical response and recovery time. It was found that the typical response time of ~54 s and recovery time of ~ 65 s. Te nanowire shows the repeatability in response and recovery time cycles. In the humidity sensing mechanism, charge transfer and proton conduction play a key role. The comparison of Te nanowires based humidity sensor with other oxides material-based humidity sensors reported in the literature is listed in (Table 1).

The typical cyclic voltagrams (CV) obtained for Te nanowires on successive addition of H$_2$O$_2$ are shown in Fig. 6a. The supporting electrolyte was N$_2$-saturated 1 M PBS. The pristine ITO does not show any response but Te nanowire shows the change in anodic and cathodic current. The addition of 0.25 mM H$_2$O$_2$ to 1.75 mM H$_2$O$_2$ gives a drastic change in anodic and cathodic current. Figure 6b shows the Amperometric I–t response for Te nanowires on successive addition of 50 μM H$_2$O$_2$ for every 50 s. The I–t plot clearly indicates that the material shows very fast response time while increasing the concentration of H$_2$O$_2$ and the response time is 3sec. The plot of anodic current of CV vs. H$_2$O$_2$ concentration is showed in Fig. 6c.

Conclusions

We report simple hydrothermal synthesis of Te nanowire using TeO$_2$ and PVP as a precursor. The humidity sensor based on Te NWs exhibits an excellent response, recovery, and sensitivity.
The as-synthesized Te nanowires-based sensor device is highly stable at room temperature. The Te nanowires-based H$_2$O$_2$ sensor device shows the good response time of ~3 s. The Te nanowire sensor device can be used in future commercial devices which contains the humidity and H$_2$O$_2$.

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