Nickel Cobalt Telluride Nanorods for Sensing the Hydrogen Peroxide in Living Cells

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ABSTRACT: In this study, we report about the preparation of nickel cobalt telluride nanorods (NiCoTe NRs) by the hydrothermal method using ascorbic acid and cetyltrimethylammonium bromide as reducing agents. The NiCoTe NRs (NCT 1 NRs) were characterized through use of different methods. The nonlinear optical measurements were carried out using Z-scan techniques. The results give the nonlinear absorption that arises from the prepared electrode was strong in sensing in vivo H2O2 free from raw 264.7 cells. Therefore, the binary transition metal chalcogenide based nanostructures have promising potential in live cell biosensing applications.

1. INTRODUCTION

Hydrogen peroxide (H2O2) plays a crucial role in biological systems, food, pharmaceutical industries, environmental protection, and clinical studies. H2O2 is a reactive oxygen species (ROS) which leads to various health issues, such as cancer, Alzheimer’s disease, Parkinson’s diseases, cardiovascular and neurodegenerative diseases.1-3 On the other hand, it has excellent antiseptic, oxidizing in industries, bleaching agent, and antibacterial properties. For the detection of H2O2, many analytical tools, such as fluorometric, chemiluminescent, spectrophotometric, volumetric, photometric, and electrochemical methods, were utilized. Electrochemical techniques are suitable for the amperometric determination of H2O2 because of the advantages of being cost-effective, repetitive, highly selective and sensitive, and user-friendly and having wide linear range, fast response, and lower detection limit.2-5 The electrochemical biosensor shows highly electrocatalytic activity toward the oxidation or reduction of H2O2 and achieves highly selective detection of H2O2 at the nanomolar level.5 Numerous pieces of evidence were found for an H2O2 sensor which is not sensitive for identifying H2O2 in existing cells owing to the elevated intricacy of the existing structure and also is less focused on in vivo H2O2. It has extremely high selectivity, reproducibility, and stability. It is evident that the electrochemical exposure of H2O2 is found to be hard in active cells.1

Recently, many researchers have focused on metal chalcogenide H2O2 biosensors because of their electrical conductivity, electrochemical activity, enlarged electrocatalytic sites due to the mixed valence state, and enriched redox properties. A few reports on metal chalcogenides are based on electrochemical detection of H2O2 in living cells, such as MoS2, PtW/MoS2, MoS2/CN, and NiCo2S4@CoS2. Wang et al. have fabricated MoS2 with a high sensitivity of 152 mA cm-2 M-1, RSD of 1.9% of its current response to 6.00 mM glucose, and good stability.5 Dynamic H2O2 released from mouse breast cancer cell line 4T1 monitored over a PtW/MoS2 nanocomposite electrode has been reported by Zhu et al.5 Dai et al. synthesized MoS2/CN nanowires having good catalytic performance toward H2O2 with the limit of detection 0.73 μM and the wide linear range of 2 to 500 μM.7 The NiCo2S4@CoS2 electrode displayed the sensitivity of 1.49 μA μM-1 cm-2, lower detection limit of 2 nM, and linear range of 12.64 nM to 2104 μM.1 The CoNiSe/rGO nanocomposite displays a good electrocatalytic activity against glucose with the sensitivity of 18.89 mA mM-1 cm-2, LOD of 0.65 μM, and linear range of 1 to 4000 μM.8

Semiconductor nanostructures of transition metal chalcogenides also exhibited interesting nonlinear optical properties and applications such as nonlinear absorption, nonlinear refraction and optical limiting, optical switching, pulse-shaping devices, optical communication, optical signal processing, optical storage, and mode-lockers to the extraordinary intrinsic properties benefiting from the strong confinement of excitons.9-12 There are some reports of transition metal...
Scheme 1. Illustration of the Preparation of NiCoTe NRs for H2O2 Produced by RAW 267.4 Cells

2. EXPERIMENTAL SECTION

2.1. Preparation of Nickel Cobalt Telluride Nanorods.
Starting materials such as ascorbic acid (C6H8O6), cetyltrimethylammonium bromide (CTAB), sodium telluride (Na2TeO3), nickel acetate (Ni(CH3COO)2·2H2O), cobalt acetate (Co(CH3COO)2·4H2O) from Sigma-Aldrich, and deionized water from a milli-Q-ultra pure (18.2 MΩ cm−1) system were used. Initially, CTAB was dissolved in 40 mL of deionized water with vigorous stirring to form a homogeneous solution. Then C6H8O6, 1.88 mmol of Na2TeO3, 1.25 mmol of Ni(CH3COO)2·2H2O, and 0.63 mmol of Co(CH3COO)2·4H2O salts were added to the above solution. Immediately, white TeO2 precipitate was observed. This solution mixture was stirred for nearly 30 min with the addition of 40 mL of deionized water. The solution was transferred to a Teflon-lined stainless-steel autoclave and maintained at 180 °C for 24 h. The final product was washed well with ethanol and distilled water several times to remove the excess impurities. Then it was dried to obtain the sample coded as NCT 1. Moreover, the samples coded as NCT 2 and NCT 3 were obtained by the same process with 0.94 and 0.63 mmol of Ni(CH3COO)2·2H2O and 0.94 and 1.25 mmol of Co(CH3COO)2·4H2O, respectively. Wet chemically prepared nickel cobalt telluride (NCT-W) is briefly discussed in the Supporting Information.

2.2. Characterization. Nonlinear optical properties were studied using a Nd:YAG laser (532 nm, 9 ns, 10 Hz) by the Z-scan technique. NiCoTe nanorod powder was sonicated for 1 h before the laser excitation, and it was taken into the 1 mm quartz cuvette. The electrochemical investigations were made using a CHI 1205A workstation, Amperometric measurements were performed using an analytical rotator AFM6RX (PINE instruments) with a rotating disc electrode (RDE, area = 0.24 cm2), and electrochemical impedance spectroscopy (EIS) studies were carried out using an EIM6ex Zahner instrument for biosensing applications.

2.3. Electrochemical Measurements. 2.3.1. Sensor Studies. The electrochemical experimentation was performed through a predictable three electrode cell such as NiCoTe/GCE as a functioning electrode (area 0.071 cm2), saturated Ag/AgCl (saturated KCl) as a reference electrode, and 0.1 M phosphate buffer (PB) as a sustaining electrolyte. The customized electrodes were equipped on the glassy carbon electrode (GCE) plane through a simple drop emitting stratagem. Initially the GCE surface was precleaned through cycling amid 0.0 and 0.8 V, in 0.1 M PB (pH 7) used for 10 cycles at a scan velocity of 50 mV/s. Seven microliters of NCT 1 was plunged on the precleaned GCE and dehydrated at ambient warmth. Preceding every electrochemical trial the electrolyte results were deoxygenated along with prepurified nitrogen gas for 15 min.

2.3.2. Cell Culture to Cultivate Mammalian Cells. Unprocessed 264.7 cells (murine macrophages) were matured in 5% CO2 in a 12.5 cm2 urn with Dulbecco’s tailored Eagle’s medium (DMEM) along with 1% antibiotics (100 U/mL penicillin and 100 μg/mL streptomycin (GIBCO, LOT198 9515, NY, USA)) and 10% (v/v) fetal bovine serum (FBS) at 37 °C. The 90% matured combined cells flow together, and the processed cells were frayed and composed in the course of centrifugation for 15 min at 1500 rpm. Subsequently the cells were rinsed with 0.01 M phosphate buffer saline for numerous periods. The number of cells was calculated via a hemocytometer. To kindle the fabrication of H2O2 from unrefined 264.7 cells, lipopolysaccharide (LPS, 97%), a prominent stimulant of H2O2, was inserted into the cell solution.

3. RESULTS AND DISCUSSION

Structural and morphological studies, such as XRD, XPS, BET, and TEM, for the prepared samples have been analyzed and
discussed in our previous report. Figure S1(a,b) displays the FESEM images of NCT 1 and NCT W. The prepared materials show uniform morphology of nanorods. Figure S1c reveals the the XRD pattern for NCT-W corresponds to nickel telluride [International Centre for Diffraction Data (ICDD) number 00-065-3665] and cobalt telluride (ICDD number 00-089-7180). The diffraction peaks at 26.91, 27.68, 32.13, 40.57, 41.49, 43.49, 51.23, 63.05, 65.94, 67.85, and 75.73° are assigned for nickel telluride. The peaks at 27.68, 32.13, 35.00, 39.98, 37.93, 40.57, 49.71, 56.81, and 71.62° are assigned for cobalt telluride.

3.1. Optical Limiter. The change in absorption of a material induced by an intense laser beam is measured by the open aperture (OA) Z-scan technique at 532 nm under nanosecond laser excitation to obtain the nonlinear absorption coefficients. The OA Z-scan traces of NCT composites at 150 μJ (Figure 1a) demonstrate the presence of a valley-like pattern (decreased transmission) near the focal point indicating reverse saturable absorption (RSA). The experimental data strongly rely on the 2PA equation with a weak influence. The OLT curves for the composites. 19 Vineeshkumar et al. reported that the effective 2PA cross section for ZnFeS.18 rGO-PbS shows better optical limiting behavior due to the two photon induced FCA phenomenon. In the present work, it is found that the higher β for NCT 2 compared to the other metal chalcogenides is due to the combination of effective 2PA and FCA.

The cyclic voltammograms (CVs) of bare GCE and NCT 1/GCE electrodes measured at the scan rate of 5 mV/s in the potential window of 0 to −0.8 V using 0.05 M PBS are shown in Figure 2a. The NCT 1 modified electrode displays a cathodic peak current at −0.52 V that reveals the significant electrocatalytic activity upon H2O2 reduction. Figure 2b reveals the CV response of NCT 1/GCE in PBS containing 1 mM H2O2 at a scan rate from 10 to 100 mV/s. The cathodic peak current increases with the lower to higher scan rate. The plot between the cathodic peak current and the square rate of the scan rate exhibits good linearity with the correlation coefficient (R2) 0.9815 indicating a diffusion-controlled reduction process.

Figure 1. NCT 1, NCT 2, and NCT 3 at 150 energy of nanosecond laser excitation: (a) open aperture Z-scan; (b) optical limiting curves.

Table 1. Comparison Table for the Third Order Nonlinear Optical Parameters of the Metal Tellurides with Some Other Metal Chalcogenides

| Sample     | Energy (μJ) | Nonlinear absorption (β) (m/W × 10−16) | Optical limiting (J/cm²) | Ref |
|------------|-------------|----------------------------------------|---------------------------|-----|
| Te         | 100         | 0.27                                   |                           | 19  |
| Te/C       | 0.92        |                                        |                           |     |
| ZnFeS      | 60          | 2.0                                    | 2.6                       | 18  |
|            | 100         | 2.3                                    | 2.1                       |     |
| rGO-PbS    | 25          | 7.9                                    | 2.3                       | 20  |
| CuS NPs    | 16          | 1.4                                    |                           | 21  |
| CuS QDs    | 4.9         | 2.3                                    |                           |     |
| NCT 1 NRs  | 150         | 4.8                                    | 3.99                      | Present work |
| NCT 2 NRs  | 11          | 1.80                                   | 1.80                      |     |
| NCT 3 NRs  | 4.1         | 3.68                                   |                           |     |
Figure 2c). Figure 2d represents the CV of the NCT 1/GCE electrode for concentrations of H$_2$O$_2$ ranging from 20 to 160 μM. The cathodic peak current increases linearly as the concentration of H$_2$O$_2$ increases. Figure 2e illustrates chronoamperometry (CA) of the NCT 1/GCE electrode after the injection of concentrations of H$_2$O$_2$ at regular intervals into the stirred PBS at the applied potential of $-0.52$ V. The steady state current has been reached in 5 s, indicating a fast response behavior with the linear increase of H$_2$O$_2$ concentration for the range of 0.02 to 1835 μM. A plot between H$_2$O$_2$ concentration and current exhibits a good linearity with the sensitivity of 3464.7 μA mM$^{-1}$ cm$^{-2}$ and the LOD of 0.02 μM (inset of Figure 2e). The selectivity of the electrode in H$_2$O$_2$ detection has been tested in the presence of common interfering agents such as 0.5 mM dopamine (DA), uric acid (UA), ascorbic acid (AA), and folic acid (FA) in PBS at a $-0.52$ V potential (Figure 2f). The electrode quickly responds to H$_2$O$_2$, but it is not sensitive to other species. The NCT 1/GCE electrode displays an excellent selectivity toward H$_2$O$_2$. Hydrothermally prepared NiCoTe shows higher sensitivity, linear range, and limit of detection than wet chemically prepared NiCoTe. The sensitivity, linear range, and limit of detection for the prepared materials and some other metal chalcogenides are listed in Table 2.

The electrochemical characteristics of NiCoTe-W NRs were analyzed through CVs using Na$_2$fi on as a binder in deoxygenate PBS. Figure S2a gives the voltammograms recorded on bare GCE and NCT-W/GCE at different scan rates. Figure S2b reveals the CV response of NCT W/GCE PBS at scan rate from 10 to 100 mV/s. Figure S2c show the current response of a NCT-W/GCE modified electrode with different concentrations of H$_2$O$_2$ ranging from 45 to 180 μM. With the addition of H$_2$O$_2$ the peak current increases from 0.514 to 0.528 mA. Figure S2d displays the CA response of the NCT-W/GCE modified electrode where it shows a quick response to the concentration of H$_2$O$_2$. While maintaining PBS in a stirring condition, different concentrations of H$_2$O$_2$ are added at regular intervals. The CA analysis was studied on the chemically modified electrode by applying a constant potential of $-0.4$ V.

The calibration curve for the sensor was obtained by plotting the current $I$, measured for each hydrogen peroxide addition, against concentration. Two main behaviors can be identified (Figure S2e); the first at low H$_2$O$_2$ levels (5−25 μM) was

![Figure 2](https://pubs.acs.org/acsomega/article-figures/110121acsomega.1c06007.jpg)

Table 2. Comparison of the Different Modified Electrodes for Electrochemical Sensing of H$_2$O$_2$

| Sample | Sensitivity ($\mu$A mM$^{-1}$ cm$^{-2}$) | Limit of detection (μM) | Linear range (μM) | ref |
|--------|----------------------------------------|-------------------------|-------------------|-----|
| Te     | 757                                    | 28.4                    | 0.67−8.04         | 2   |
| CdTe   | 1326                                   | 0.1                     | 0.67−8.04         | 13  |
| CoS/RGO| 2.519 μM                               | 0.042                   | 0.1−2542.2        | 3   |
| PdW/MoS$_2$ | 1.71 μM               | 0.005                   | 1−200             | 6   |
| NiCoS$_2$@CoS$_2$ | 1.49 μM | 0.002                   | 0.1264−2104       | 1   |
| NiS    | 82.73                                  | 5.2                     | 10−870            | 22  |
| NCT W  | 93.428                                 | 0.01                    | 5−25              | Present work |
| NiS    | 93.428                                 | 0.17                    | 30−100            | |
| NCT 1  | 3464.7                                 | 0.02                    | 0.02−1835         | |

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relevant to a linear variation of $I$ toward concentration with a considerable slope (93.42 μA μM$^{-1}$ cm$^{-2}$) with the detection limit of 0.01 μM; the second was observed at higher H$_2$O$_2$ concentrations (30–100 μM) with a slight decrease in sensitivity (6.93 μA μM$^{-1}$ cm$^{-2}$) with the detection limit of 0.17 μM being obtained with a response time of 5 s. The anti-interference ability has been tested using the most common interfering species, including AA, H$_2$O$_2$, oxalic acid (Ox.A), DA, glucose (GC), UA, and fructose (FT) (Figure S2f). The current response does not change after addition of the same concentration of AA, Ox.A, DA, GC, UA, and FT. These results indicate that the modified NCT-W/GCE electrode performs a good selectivity toward H$_2$O$_2$, and it has the ability to reduce the interference from the electroactive species.

To evaluate the stability of the NiCoTe/GCE modified electrode, it was monitored every day while the electrode was kept in PBS (pH 0.7) over the time interval of 3 weeks. The electrode retained 92% of its initial current even after 3 weeks of continuous usage, revealing good durability. For ensuring reproducibility, tests were performed with five different NiCOTe/GCE electrodes in the presence of H$_2$O$_2$, which exhibited the relative standard deviation (RSD) of 3.48%. The sensor has suitable storage stability toward H$_2$O$_2$ sensor applications.

With the aid of cell culture equipment, RAW 264.7 cells were matured and then shifted into an electrochemical cell which consists of 2 × 10$^6$ cells balanced in 20 mL of broth medium (pH 7.0). Subsequently the amperometric testing (electrode potential = −0.52 V vs Ag/AgCl) in hydrodynamic conditions (electrode rotation speed 1500 rpm) was performed. Figure 3a shows an increase in the sturdy

Figure 3. Real sample analysis amperometric response of the NCT 1/GCE electrode in a supporting electrolyte containing (a) RAW 264.7 cells with injection of LPS stimulant or (b) human serum sample injected with laboratory sample ((a) 1 μM H$_2$O$_2$ and (b) 1 μM H$_2$O$_2$ spiked).

demonstrate that the NCT 1/GCE electrode can be used for the detection of H$_2$O$_2$ and could be useful for physiological and pathological studies. Scheme 2 describes H$_2$O$_2$ release from RAW 267.4 living cells detected by the developed electrochemical sensor. This illuminates that the NCT 1/GCE NRs provide a promising platform to monitor H$_2$O$_2$.

4. CONCLUSION

NiCoTe was successfully synthesized through the hydrothermal method. The optical limiting and nonlinear absorption coefficients were calculated by Z-scan measurement at the nanosecond pulse of the Nd:YAG laser. NCT 2 gives the optical limiting threshold and nonlinear absorption coefficient of 1.80 J/cm$^2$ and 11 mW × 10$^{-10}$. A good sensitivity (364 μA mM$^{-1}$ cm$^{-2}$) and response time (5 s) at the detection limit 0.02 μM revealed that the electrode can be used for the detection of cellular level H$_2$O$_2$. NCT 1 effectively identified and quantified H$_2$O$_2$ release in real time from RAW 264.7 cells. Furthermore, this work demonstrates that the synthesized material offers a new possibility to achieve the best optical limiter.

ASSOCIATED CONTENT

Supporting Information
The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acsomega.1c06007.

Detailed Experimental Section and electrochemical measurements for biosensor studies, FE-SEM images of NCT-1 NRs and NCT-W, XRD image of NCT-W (Figure S1), and cyclic voltammetry and chronoamperometric analysis of NCT-W (Figure S2) (PDF)

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Notes

The authors declare no competing financial interest.

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