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Room temperature selective sensing of aligned Ni nanowires using impedance spectroscopy

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Abstract

Room temperature gas sensing behavior of arrayed one-dimensional (1D) nickel nanowires (Ni NWs) are investigated using impedance spectroscopy. Ni nanowires synthesized via electrochemical deposition method based on anodic aluminum oxide (AAO) templates. Their structural characterization verified by scanning electron microscopy (SEM), x-ray diffraction (XRD), and Fourier transform infrared spectroscopy (FT-IR) analysis. Impedance spectroscopy as an essential technique utilized to understand the mechanism of gas interaction with the wires through the changes in their electronic behavior. Bode and Nyquist plots with the real and imaginary impedances are plotted versus frequency range of 500 Hz to 2 MHz at different relative humidity values (varying from 30% to 70%) and ethanol vapor concentrations (varying from 2 to 18 ppm). The equivalent circuits are proposed and simulated for impedance responses to both humidity and ethanol vapors. The impedance plots indicate the increase in resistance of the aligned nanowires at low frequencies by the adsorption of water and ethanol molecules.

1. Introduction

Volatile organic compounds (VOCs) such as ethanol, methanol, acetone, and formaldehyde are toxic, harmful and flammable gases that widely used in the modern chemistry industry [1–3]. So, to create a safe and healthy atmosphere, detection and control of their pollution are an important approach. Among various types of gas sensors, the resistive-type are common because of their stability, excellent performances, low cost, and simplicity of their operation [4–7]. It is known that size, surface structure and morphology of the sensing materials greatly influence their performances; hence, many efforts have been applied to synthesize gas sensors with various morphologies and surface structures [8–12]. One-dimensional (1D) nanowires can exhibit excellent gas sensing performance due to providing high surface area [13]. Several synthetic methods such as template-assisted electrochemical deposition, electro-spinning, hydrothermal and sol-gel process have been reported for the fabrication of nanowires [14–16]. Among these methods, template-assisted electrochemical deposition is a relatively cost-efficient straightforward technique with a controlled diameter. It typically operates at ambient temperature and pressure as well as can be used for mass production of nanostructures with controlled geometry and morphology. Additionally, among various templates, anodized aluminum oxide (AAO) has become one of the most commonly applied in fabricating the relatively straight nanowires.

On the other hand, understanding the mechanisms that determine these materials’ gas-sensing performance is crucial to advance their applications. The direct current (DC) measurement provides information on resistance variation after exposure to gas (gas sensitivity). Alternative current (AC) measurement which is rarely used by researchers can give the same information as DC measurement, but also allow understanding contributions from the bulk, surfaces and interfaces, grain boundaries, electrode contacts and even substrate
whether we work with polycrystalline materials or single-crystal structures such as nanowires and nanorods [17]. Impedance spectroscopy (IS) is known as a powerful measurement technique in understanding the mechanism of interactions based on a physical and chemical process that affects the electronic behavior of the materials [17–24]. A small AC voltage with variable frequency will be applied to measure the impedance that is defined as the ratio of the complex voltage to the complex current. The equivalent circuit is commonly used for relating the impedance data to the physical system but compares with DC measurements; this technique is lesser used because of the complexity of proper data interpretation. Although nanowires based gas sensors have been investigated to an extent [13], the IS techniques are not fully developed on these devices. This work presents the IS data for the aligned Ni nanowires, including data interpretation based on fitting models commonly used to enable a better understanding of the materials systems. Ni nanowires have presented interesting applications in various fields, such as magnetic materials [25–28]. We use Ni NWs as a ferromagnetic material to create well-aligned nanowires and taking advantage of their surface to volume ratio. Ni NWs were fabricated by electrochemical deposition method using alumina membranes (AAO). Aligned nanowire sensors prepared by dispersing a suspension of concentrated nanowires onto a substrate with pre-patterned electrodes in the presence of a magnet. The crystalline nature and morphology of the prepared samples were determined by X-ray Diffraction (XRD) Panalytical X’Pert Pro diffractometer operating at 40 kV and 30 mA and field-emission scanning electron microscopy (SEM), model FEI NOVA NANOSEM 450. The changes in the impedance upon humidity and ethanol vapor adsorption were recorded at room temperature using an NF FRA5087 frequency response analyzer with frequencies ranging from 500 Hz to 2 MHz. In the following, the fitting of the impedance data to the equivalent circuit was performed using a complex nonlinear least squares Levenberg-Marquardt algorithm implemented in a software package (EIS spectrum analyzer software). The variation in the resistance by the gas adsorption represents the overall charge transport of a complicated network of interconnected nanowires including bulk, junctions and electrodes. The used IS method and the AC analysis yield a simple electrical circuit model that help understanding the conduction mechanisms and the contribution of each part of our sensing material.

2. Experimental method

2.1. Ni nanowire growth

The template-assisted electrochemical deposition was employed to grow the Ni nanowires using hard anodization aluminum oxide (HA-AAO) template at ambient temperature. Highly pure aluminum foil (99.999%) was cut into small discs (10 mm diameter, and 0.3 mm thickness), ultrasonically degreased by acetone and electro-polished to diminish the roughness of the alumina surface by applying ethanol: perchloric acid 4:1 at 0 °C, and 100 mA cm−2 for 5 min. The hard anodization performed in 0.3 mol l−1 oxalic acid aqueous solution in a constant voltage of 40 V for 5 min at 0 °C. This process forms a protective oxide layer on the surface of the aluminum substrate to suppress breakdown and burning effects. Afterward, the anodization voltage was systematically increased to 130 V at a rate of 0.5 V s−1 and continued for 60 min to form the pores with the desired length. To thin the created barrier layer, the voltage was exponentially decreased from 130 to 40 V. The nanopores were also widened by etching using 0.3 mol l−1 phosphoric acid solution at 32 °C for 100 min. The re-anodizing of anodic alumina was conducted at 40 V for 5 min in 0.3 mol l−1 oxalic acid at 17 °C and then, the voltage was systematically decreased to 10 V. This caused a penetration in the barrier layer at the bottom of the holes to remove or reduce its thickness for any subsequent electrodeposition of Ni.

The synthesis of the nanowires was carried out using a conventional two-electrode potentiostatic cell. The AAO template was covered with copper as a cathode placed in parallel with the graphite plate as an anode in an electrodeposition bath. The 0.3 mol l−1 NiSO4·6H2O and 40 g l−1 H3BO3 were used as the basic components of electrodeposition bath solution. During the electrodeposition, the electrolyte was continuously agitated by a stirrer, and the pH value of the solution was kept at the value of 3.5. While the deposited nanowires overflowed from the nanoholes, the electrodeposition process was stopped. To free nanowires, the AAO dissolved by immersing in a 2 mol l−1 NaOH solution. Then the nanowires were cleaned and dispersed in deionized water.

2.2. Preparation of the sensors based on aligned Ni nanowires

The Ag electrodes were sputtered on a glass substrate through a delicately-designed shadow mask with an interdigitized comb-like shape. The width and length of each finger were about 0.27 and 4 mm, respectively, and the electrode inter-spacing was 0.25 mm. The glass substrates with pre-patterned Ag interdigitated electrodes (IDE) were located on a magnet. Then, a few small drops of the concentrated suspension of the nanowires were drop casted on the electrodes. The presence of the magnet assisted in aligning the ferromagnetic Ni nanowires into a preferential orientation. An annealing process at 100 °C performed for better adherence of the nanowires onto the substrate as well as improving their interfacial contacts and also, to eliminate any organics left by the solvent.
This architecture has hundreds to many thousands of nanowires well oriented with many nanowire-nanowire and nanowire-electrode interfaces.

The schematic of the sensing set-up is illustrated in figure 1. As displayed, the static sensing measured at room temperature (25 °C) using an electrochemical impedance analyzer (EIS). The prepared sensors were placed on top of a bowl and connected to an EIS spectrum analyzer. The sensing performance was tested at different humidity and at a variety of ethanol vapor concentrations at room temperature. A voltage of 50 mV AC signal which overlapped on a 0.5 V DC applied to devices. The variations in the impedance in exposure to humidity and alcohol vapor versus frequency were collected and then fitted using the EIS spectrum analyzer software. The humidity and alcohol vapor were both generated by the well-controlled flow of dry air into the bowl including only DI water for humidity and a mixture of ethanol/DI water for alcohol vapor generation. The humidity was controlled by placing a hygrometer close to the devices. Different concentrations of alcohol vapor prepared by mixing different volume ratios of absolute ethanol (from Merck Ltd, 99.9%) and DI-water (18 MOhm-cm) and the concentration of ethanol in ppm was calculated according to Henry’s law [29, 30].

3. Results and discussion

3.1. Characterization results

Figure 2(a) shows a cross-sectional SEM image of Ni nanowires in an HA–AAO template. Figure 2(b) and c present the out-template wires with a length of ∼40 μm and a mean diameter of ∼145 nm. According to the XRD peaks, the wires were determined to be crystalline with a face-centered cubic (FCC) crystal structure shown in figure 2(d). It shows three diffraction peaks corresponding to (111), (200) and (220) crystal planes, respectively. Figures 2(e) and (f) are the optical microscope images of the device after the deposition of the Ni nanowires. As shown, the Ni nanowires with a length of 40 μm aligned between interdigitated electrodes with an inter-electrode distance of 100 μm.

Also, we devoted attention to the behavior of the stretching bands of OH, C–O, and C–H of adsorbed ethanol on the surface of the Ni nanowires utilizing FTIR spectra in the wavenumber region 500–4000 cm⁻¹. Figure 3 demonstrates the IR absorption spectra of Ni nanowires exposed to ethanol compare to the case when the sample is in environmental condition at 30% RH to evaluate the intensity ratio of the adsorbed stretching bands on the surface. The wide and non-homogeneously broadened band stretching line of OH-groups apparently seen in the region 3000–3800 cm⁻¹ for both Ni nanowires before and after the ethanol exposure. The adsorbed water molecules at room temperature are responsible for the wide band of OH for Ni nanowires before ethanol exposure. Upon exposing to ethanol, this region with other adsorption wavenumber of 1048 cm⁻¹ is seen which is corresponded to C–O stretching bands in ethanol. The wavenumber of 426 cm⁻¹ assigned to the Ni stretching band of nanowires.

3.2. Impedance spectroscopy

3.2.1. Humidity sensing

Since atmospheric air contains a considerable quantity of water vapor, it is necessary to consider the interference of humidity and investigate the effect of humidity level on the sensing performance of the sensor. Understanding the effect of humidity on sensing mechanisms is crucial to advance their applications. Initially, the impedance
Figure 2. SEM images of in-template (a), out-template Ni nanowires (b) and (c), and XRD patterns of the out-template Ni nanowires (d), optical images of the aligned Ni nanowires (e) and (f).

Figure 3. The IR absorption spectra of adsorbed water and ethanol on the Ni nanowires within the region of C–H and OH stretching bands.
data of the aligned Ni nanowires in relative humidity of 30% RH (the environment humidity) presented in figures 4(a)–(c) in several forms of Bode and Nyquist plots.

The direct current (DC) measurement provides information on resistance variation after exposure to gas. Alternative current (AC) measurement which is rarely used by researchers can give the same information as DC measurement. Besides, it clarifies the contribution from the bulk, surfaces and interfaces, grain boundaries, electrode contacts and even substrate whether it is polycrystalline material or single-crystal structure such as nanowires and nanorods [17]. Bode plot includes the modulus (|Z|) and phase (Θ) and Nyquist plot includes the imaginary (Z′) and real components (Z′′). Both plots are needed in order to determine the electrical behavior in the aligned Ni nanowires affected by elements such as bulk, boundaries/junctions of the material, and the electrodes. The used Nyquist plot yield a simple electrical circuit model that leads to understand the conduction mechanism and the contribution of each part of our device including bulk, junctions and electrodes toward variation in the DC resistance due to gas adsorption. This represents the overall charge transport of a complicated network of interconnected nanowires. To further explain the potential sensing mechanism of the Ni nanowires, Bode diagrams were also investigated. Equations (1)–(3) represent the impedance, its modulus as well as the phase angle:

\[ Z(\omega) = Z'(\omega) + jZ''(\omega) \]  
\[ |Z| = \sqrt{(Z')^2 + (jZ'')^2} \]  
\[ \theta = \tan^{-1}\left(\frac{Z''}{Z'}\right) \]

As shown in figure 4(a), the impedance modulus decreases with an increase in frequency which is an indication of mix capacitive and resistive behavior [17]. Also, by increasing frequency, the phase difference plot moves toward a lower angle. The charge carriers that are moving through the aligned nanowires have to overcome the impedances of two different regions. One of them is the bulk of the material and the other is the boundaries between nanowires’ interfaces where the different dielectric properties would occur. High frequencies make a fast alternating current which can most efficiently displace charges. But at the low frequencies, the traveling of charge carriers is blocked at the nanowires’ interfaces including nanowire-nanowire or nanowire-electrode junctions. As evident from the Bode plots, at a lower frequency, the behavior is resistive, and at a higher frequency, it moves towards capacitive. In our sensor with applied potential, the current chooses the path of least impedance to travel from one electrode to the other. At lower frequencies, the impedance of the capacitor increases due to its inverse dependence on frequency and the current prefers to flow through the resistor (junctions). It is vice versa at high frequencies; the impedance to current in the capacitor is smaller than the impedance of a resistor (which is constant at all frequencies), so the capacitive behavior is dominant.
Figure 4(b) is a plotting of the imaginary part of impedance against frequency which has a peak at the value of relaxation frequency. The relaxation frequency is defined as the value where the charge carriers have to overcome the impedances of two different regions of the bulk and the boundaries. Also, a circuit has a relaxation frequency at the value where the currents switch from one element of the circuit to the other [17]. The semicircle impedance spectroscopy (Nyquist plot) in figure 4(c) shows the imaginary part of the impedance ($-Z''$) versus the real part, ($Z'$) with a center depressed below the real axis. As displayed, the points are the experimental data, and the solid line represents the fitting curve using the Levenberg-Marquardt algorithm of the EIS Spectrum Analyzer. As shown in the inset, the fitting resulted in an equivalent electrical circuit model as well as the impedance formula. The equivalent electrical circuit includes a resistor ($R$) in parallel with a capacitor ($C$), each representing a physical part of the device that has resistance and an alternating-current capacitance. In an ideal case, the Nyquist plot can take the form of a series of semicircles each representing one separate electrical phenomena attributed to the bulk material, grain boundary effects and the electrode phenomena [17]. Also, each semicircular arc has a characteristic maximum occurring at a unique relaxation frequency. In our data, the Nyquist plot appears as one semicircle which corresponds to the case when all of the possible electrical behavior occurring in the material including the electrical process through the bulk, junctions, and the electrode has similar relaxation frequencies [17]. Also, it can be attributed to several other reasons that are beyond our measurement frequency range. Also, this can happen if the constant $RC$ of this process is small, yielding a large relaxation frequency. Finally, the constants of the bulk and the boundary process can be similar to each other and both arcs are overlapping. It results in an arc depressed in the middle. The total impedance of the equivalent RC parallel circuit is according to equations (4) and (5):

$$\frac{1}{Z} = \frac{1}{Z_R} + \frac{1}{Z_C}$$  \hspace{1cm} (4)

$$|Z|^2 = \frac{R^2}{1 + \omega^2RC^2}$$  \hspace{1cm} (5)

Also by using the equation of a circle, we can model equation (5) as a circle with radius $R/2$ which is centered at $R/2$, equations (6) and (7):

$$x^2 + (y - \frac{R}{2})^2 = \frac{R^2}{4}$$  \hspace{1cm} (6)

$$x^2 + (y + \frac{R}{2})^2 = \frac{R^2}{4}$$  \hspace{1cm} (7)
The semicircle in figure 4(c) suggests a contribution from the parallel combination of charge transfer resistance (R) and the frequency independent capacitance (C). From both Bode and Nyquist plots, we conclude that the C is due to interfacial capacitance and R is a result of the charge movement through junctions between nanowires.

Figure 5 shows the Bode and Nyquist plots of the aligned Ni nanowires at a different relative humidity of 30, 50 and 70% RH. As illustrated, the modulus impedance increases monotonically upon an increase of humidity from 30 to 70% RH, indicating resistance and capacitance enhancement (figure 5(a)). The phase angle plot shows a shift in the phase difference towards a lower angle which is an indication of an increase in the capacitive behavior with an increase in the humidity (figure 5(b)). As shown in figure 5(c), the maximum of $Z''$ (peak height) increases with an increase in humidity, which is because of higher polarization in the presence of the water molecules. Also, a decreasing shift in relaxation frequency by increasing humidity is observed which equals an increase in relaxation time ($\tau$). This statement can be supported by considering the inverse relationship between relaxation time and frequency ($f = 1/2\pi\tau$). And it is also attributed to higher polarization at higher humidity which increases the capacitance. According to equation (7), the semicircles in figure 5(d) show the impedance of the sensor increases with humidity content by the large change in the arc radius which indicates the increase in R.

3.2.2. Ethanol sensing
We measured the impedance response of the aligned Ni nanowires in exposure to ethanol vapor with concentrations of 2 to 18 ppm at a constant humidity of 50% RH. Figure 6 shows the impedance spectroscopy, Bode (a), and (b) and Nyquist (c) and (d) plots of the aligned Ni nanowires measured at room temperature. The impedance modulus increases considerably and the phase difference plot moves toward a lower angle with an increase in the ethanol concentration. The shifts in impedance and phase angle in ethanol environment are larger than in humidity media. The AC responses of Ni nanowires in complex impedance at different concentrations of ethanol show that maximum in $Z''$ becomes larger and shifts to lower frequencies as the ethanol concentration increases resulting in larger relaxation time. This is also attributed to higher polarization at higher alcohol concentrations which cause an increase in the capacitance.
Accordingly, the response of the sensor is defined as $R_{\text{air}}/R_{\text{ethanol}}$, where $R_{\text{ethanol}}$ and $R_{\text{air}}$ are the measured resistances in exposure to ethanol and the atmosphere, respectively [31]. Response as a function of ethanol flow rate (ppm) at room temperature (∼25 °C) displayed in figure 7. It could be seen that the responses increase as alcohol vapor concentration increases up to about 18 ppm.

The fitted experimental data with the proper equivalent circuit resulted in the values of $R$ and $C$ as given in table 1. The capacitance did not change much by exposing it to humidity and different ethanol vapors. Our synthesized nanowires have a very small cross-sectional area with a distribution of 100–200 nm in diameter and 10–40 μm in length, so their associated capacitance can be well around the order of pF ($10^{-12}$ F). This amount of capacitance usually hidden between experimental noise (depending on the frequency can be in the order of several nF) and the substrate capacitance. The substrate capacitance depends on the thickness of the substrate and the inter-electrode distance, can be in the hundreds of pF [17]. The presence of substrate capacitance and noise which sum in parallel with the nanowire capacitance, make it difficult to isolate and properly model the nanowire capacitance. The total extracted capacitance of the substrate and the capacitance of the aligned nanowires are at the order $10^{-10}$ F.

A considerable increase in the resistance ($R$) obtained by exposing to 70% RH and 18 ppm ethanol at 50% RH. It relies mostly on the adsorption on the surface and at the junctions of the nanowires.

![Figure 7. Responses of the sensor based on the aligned nanowires versus different ethanol concentrations at 50% RH (25 °C).](image)

![Figure 8. Schematic representation of a Nyquist plot (a). All three contributions in the electrical behavior are present with an ideal circuit model in the associated frequency range: bulk, junction and electrode elements, each represented as a parallel RC circuit; the sensor responses to ethanol, humidity, H₂, CO and CH₄ indicating selective response toward target gases (b).](image)

| Environmental Condition (30% RH) | 70% RH | 18 ppm Ethanol at 50% RH |
|----------------------------------|--------|-------------------------|
| $R$ (Ohm)                       | 1312.7 | 1972.4                  | 3576.2 |
| $C$ ($10^{-10}$ F)              | 1.3078 | 1.3952                  | 1.36   |

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A considerable increase in the resistance ($R$) obtained by exposing to 70% RH and 18 ppm ethanol at 50% RH. It relies mostly on the adsorption on the surface and at the junctions of the nanowires.
Table 2. Comparison of the sensing performance of the developed sensor compared with previously published resistive ethanol gas sensors.

| Material                               | Synthesis method     | Sensitivity ($R_g/R_a$) | Concentration (ppm) | Temperature (°C) | Relative humidity | References |
|----------------------------------------|----------------------|-------------------------|---------------------|------------------|------------------|------------|
| Nickel oxides nanowires                | Nanocasting          | 5.26                    | 100                 | 300              | 65%              | [35]       |
| Multiple networked NiO nanostructures  | Hydrothermal         | 45                      | 200                 | 300              | Air              | [36]       |
| Stannum(Sn)-doped NiO nanowires        | Nanocasting method   | 15.60                   | 100                 | 340              | 45%              | [37]       |
| In$_2$O$_3$-decorated NiO hollow spheres | Ultrasonic spray pyrolysis | 9.76                   | 5                   | 350              | Air              | [38]       |
| Lance-shaped CuO nanostructures        | Hydrothermal         | 9.1                     | 100                 | 300              | Dry air          | [10]       |
| RGO-SnO$_2$ nanocomposite              | Solvothermal         | 43                      | 100                 | 300              | 98%              | [39]       |
| α-Fe$_2$O$_3$ nanoparticles            | Pechini sol-gel      | 10                      | 100                 | 225              | Dry air          | [4]        |
| ZnO thin film                          | Magnetron sputtering | 15                      | 50                  | 300              | Dry air          | [9]        |
| ZnO nanospheres                        | Laser ablation in liquid | 19                     | 250                 | 20               | Air              | [8]        |
| Ni Nanowires                           | Electrochemical deposition | 2.72                   | 18                  | 25               | 50%              | This work |

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To understand the electrical behavior of the samples in exposure to humidity and ethanol vapors, the contributions from the nanowire-nanowire (junction) resistance and the nanowire bulk resistance are considered according to the obtained IS plots. Figure 8(a) shows a schematic representation of a Nyquist plot in an ideal case that all three contributions in the electrical behavior are present with an ideal circuit model in the associated frequency range: bulk, inter-wire junction and electrode elements, each represented as a parallel RC circuit. In an ideal Nyquist plot, the lower semicircle plot is assigned to the material-electrode interface resistance, the middle is related to junctions and the semicircle at higher frequencies is assigned to the bulk of the material. But as discussed above, the Nyquist plot appears as one semicircle which corresponds to the case the dominant electrical behavior occurring in the material junctions rather than bulk and the electrode. From the Bode plots, figures 5(a) and (b) and 6(a) and (b), the characteristics of our sensor can be determined by the capacitive response at high frequencies and the resistive response at low frequencies. Increasing the relative humidity corresponds to the increase in the numbers of physisorbed layers of water over the surface of material especially at junctions. At low frequencies, the increase in the resistance mostly observed at interfaces with a smaller change in the bulk resistance. When the sensor is exposed to humidity, the water molecules at the junctions form an accumulation layer around the contact point with resistance in parallel to the resistance of nanowires with a resistivity of 18 MOhm-cm for deionized water, blocking the direct and efficient electron transport. Also, it clearly observed that, at high frequencies, the change in the impedance of the nanowires with RH is negligible. The reason can be interpreted as that the adsorbed water molecules cannot be polarized with a rapid change of electrical field at higher frequency [32], so capacitance of the nanowires does not change considerably with humidity. Figure 8(b) shows the selective response to humidity, ethanol at room temperature while there is no significant response to other gas species such as H2, CH4, CO. Shcherbakov et al analyzed and reported the high-frequency (HF) electric conductivity of mixtures of water with methanol, ethanol, and acetone separately [33, 34]. They observed the conductivity decreased at increasing alcohol content in the mixture and passed through a maximum at 2455 MHz. Ethanol is less polar than water because it has covalent bonds with no net charge. Water has a polarity index of 10 with a dielectric constant of 80 and ethanol has a polarity index of 5 with a dielectric constant of 24.5. So, the measured increase in impedance of the sensor in exposure to ethanol should be higher than water’s as we observed.

In table 2, a summary of sensing nanomaterials for ethanol vapor sensing is shown, and the performance of our sensor clearly emphasized and compared to other ethanol vapor sensors. The four most important characteristics are the low ethanol detection limit, working temperature, sensitivity, and relative humidity. Considering this table, the response at rather a low limit of detection and working at room temperature with good response at humid air, the introduced sensor can be attractive for the development of a new efficient sensor for ethanol sensing.

4. Conclusion

Here, Ni nanowires usable for ethanol sensing in a humid environment are demonstrated. On the basis of AC impedance studies, it appears that ethanol affects the charge transfer resistance. The strong humidity dependence of impedance indicates that variations in charge transfer are contributing to the sensitivity. The nanowires showed ethanol sensitivity over a large amount of humidity (50% RH). The high gas sensing performance of Ni nanowire sensors described here will be a promising material towards the detection of ethanol gas in environmental supervising. The results presented herein are relevant to the development of new ethanol sensors being potentially competitive with Non-Dispersive Infrared (NDIR) technology for gas detection.

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