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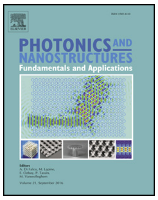

Optical dynamic range maximization for humidity sensing by controlling growth of zinc oxide nanorods

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ABSTRACT

An experimental study of the dynamic range maximization with Zinc Oxide (ZnO) nanorods coated glass substrates for humidity and vapor sensing is reported. Growth time of the nanorods and the length of the coated segments were controlled to study the differences between a reference environmental condition (normal humidity or dry condition) and water vapor concentrations. In order to achieve long dynamic range of detection with respect to nanorods coverage, several substrates with triangular patterns of ZnO nanostructures were fabricated by selective hydrothermal growth over different durations of time (5 h, 10 h and 15 h). It was found that maximum dynamic range for the humidity sensing occurs for the combination parameters of normalized length (Z) of 0.23 and normalized scattering coefficient (ζ) of 0.3. A reduction in transmittance by 38% at humidity levels of 80% with reference point as 50% humidity was observed. The results could be correlated to a first order approximation model that assumes uniform growth and the optimum operating conditions for humidity sensing device. This study provides an option to correlate ZnO growth conditions for different vapor sensing applications which can set a platform for compact sensors where modulation of light intensity is followed.

1. Introduction

Humidity is the characteristics of water vapor present in gaseous form [1]. The existence of humidity in environment significantly impacts in many areas of life including industrial production processes and health, amongst others [2]. Measurement of humidity level is necessary for many applications such as food production industries, agriculture, chemical, medical, electronics, semiconductors, civil, weather forecasting and home environment [3–7]. Thus, monitoring humidity conditions are important for a better quality of life and to improve operational and manufacturing processes in various industries [8]. Humidity sensors are characterized into two types, namely, relative humidity sensors and absolute humidity sensors. The major difference being in the sensing units is that relative humidity sensor uses the unit of relative humidity (RH) which refers to a function of temperature, while the absolute humidity is determined as a function of pressure with the measurement unit of dew/frost point (D/F PT) [9]. Changes in capacitive, resistive or thermal conductivity properties are generally used for humidity sensing [10]. In conventional electronic humidity sensors, the RH level is determined on the basis of changes in electrical conductivity or capacitance but at high humidity levels it causes electric leakages [11]. Optical sensors based on nanomaterials provide an alternative to conventional electronic transducers. Utilizing optical fibers as waveguides, information can be carried over a long distance and the transmitted signal is resistant to electromagnetic interferences [12].

Nanomaterials have unique optical, magnetic, electrical and mechanical properties which make them attractive choice for various applications such as in gas and chemical sensors, superconductors, photocatalysis, optoelectronic devices, biomedical and agricultural applications, amongst others [13,14]. Zinc oxide (ZnO), tin oxide (SnO_2) and tungsten oxide (WO_3) are commonly used as

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gas sensitive elements due to the changes in conductance upon the adsorption of gas molecules on the surface [15]. ZnO is a n-type semiconductor which has direct and wide band gap energy of 3.37 eV and a large exciton binding energy of 60 meV [16]. It also has a good optical transparency in visible spectrum which makes it useful for short wavelength optoelectronic applications [17,18]. It as well has good chemical stability, electrical conductivity, biocompatibility, and high electron transfer properties which are being utilized for electronics, optics and biomedical applications [19].

ZnO nanostructures have high surface to volume ratio which enhances the potential for the adsorption of water molecules on its surfaces when used in humidity sensing applications [20]. The optical detection of humidity levels can be based on two main factors. First is the change of the surrounding effective refractive index as well as the change of the electrical conductivity of the material due to the adsorption of water molecules [21,22]. The changes in electrical conductivity modifies the complex refractive index of the ZnO nanostructures. Combination of these two factors affects the optical scattering behavior of light incident on ZnO nanomaterials [23]. Most of optical humidity sensor studies were done on optical fibers, either silica or polymer type, where one-dimensional ZnO nanostructures such as nanorods were grown on the curved surface of the optical fibers. Growth of nanorods on flat surfaces such as glass [24], silicon wafer [25] or sapphire substrates [26] provides better control during the growth process and thus to an increase in the surface area in a smaller region for humidity sensing [27]. Due to the higher real part of the refractive index of ZnO nanorods (n_{zno} ~1.9 - ~2.1), it leads to the possibility of inducing leakage of the incident light beam when coated on lower refractive index medium, such as glass, due to scattering [28,29]. Optimization of the growth process and the coating area are crucial to enhance the sensitivity, and system performance, which leads to the reduction in the complexity of signal detection and analysis. The growth of ZnO nanostructures have been extensively reported in the literature mainly based on optimizing the synthesis parameters such as growth duration [30,31], growth temperature [32], concentration alterations [33] and solvents variation [34]. Formation of various nanostructures of ZnO like nanorods, nanowires, nanoflowers or tetrapods as well as its dimension (nanorod length, density and optical scattering cross-section etc.) varying the synthesis conditions have been reported in the literature [35,36]. This morphology of the nanostructures would affect the optical response of the coated layer such as scattering and attenuation coefficients.

Several researches have demonstrated optimization of ZnO nanorods synthesis process on optical fiber for chemical vapor detection. Fallah et al. reported the impact of the aqueous growth conditions of the nanorods on light scattering and optical fiber coupling power [37]. Bora et al. showed that 2.2 μm tall ZnO nanorods led to maximum average coupling efficiency of cladding mode light side coupling [38]. The intensity of coupled light was reported to improve upon the exposure to various chemical vapors (methanol, ethanol, toluene and benzene). In another work we have shown that the maximum side coupling of light on plastic optical fiber (POF) could be achieved on spirally-patterned of ZnO coatings [39]. The spiral-patterned coatings was found to provide better side coupling when contrasted with unpatterned coatings and optimization of the width of spiral-patterns led to maximum light side coupling which was applied for the detection of different concentrations of alcohol vapors (methanol, ethanol and isopropanol) [40].

In spite of the optimization of ZnO nanorod coatings on optical fibers successfully presented in the reports as noted above, inconsistencies in terms of optimum growth conditions related to the performance of the fabricated devices exist. Two major factors that influence this uncertainty are uniformity of the coatings and repeatability of coating structures. The sensing surface area is one of imperative factor that influence the sensitivity of a sensing device as discussed earlier. Uniformity of nanomaterial coatings guarantee a consistent sensing response throughout the surface. The reduction of the rough surface due to good uniformity of the coatings make the device suitable for being utilized as transducers, particularly in optoelectronic applications [41]. Despite the fact that a uniform coating is achievable, repeatability of the nanomaterial structures is another factor that affects the consistency of the fabricated sensor performance. Due to the sensitivity of growth processes the physical of nanostructures (e.g. length or cross-sectional area of nanorods) grown under similar growth parameters (concentrations, growth time or temperature) may not necessarily be achievable at all times. Also, the optimization of the effective area of the ZnO coating in combination with growth time may not be possible to be repeated synonymously leading to variations in batch to batch fabrication processes since minor variations in the process could lead to dramatic changes in material properties [42].

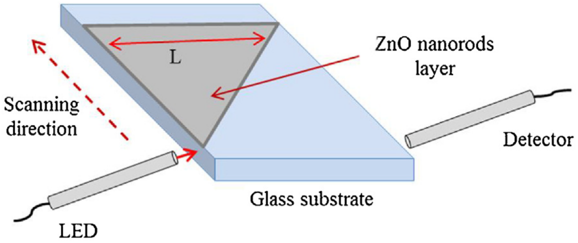

Fig. 1. Schematic representation of the fabricated device including the detection scheme.

Thus, the optimization of ZnO nanostructure growth and effective sensing surface area may not be an effective way to determine the maximum sensing response of sensor devices. In retrospect, the analysis of optimum operating conditions of fabricated sensor device delivers promising sensing device performance regardless of growth conditions or surface coverage. This implies, as long as any fabricated sensor device meets the optimum operating conditions, the device would produce best sensing performance. However, the ZnO nanorods growth time and coverage area are required to be first determined in order to realize the optimum working conditions. Thus the effect of the length of the coated ZnO nanorods depending upon the hydrothermal growth time are studied explicitly to better understand the system response over the desired limits of operation. Maximizing the effective scattering/attenuation coefficient of the nanorods layer does not necessarily result in the best performance particularly when considering intensity modulation. Instead, one needs to maximize the dynamic range of operation between two limits (i.e. dry condition or normal room humidity and maximum achievable level in the case of study) to achieve higher sensitivity.

2. Hypotheses

To realize the analysis, ZnO nanorods were proposed to be grown in triangular shape on glass substrate as shown in Fig. 1. The main purpose of the triangular form is to serve the variation of the ZnO coating length (L) along the propagation medium between the light source (LED) and detector as they move along edges of the glass substrate.

Fig.2 shows the proposed model where uniform ZnO nanorods grown on a glass substrate is considered. The coating length is L and the nanorods forward scattering coefficient is α. A light source is applied at one end of glass substrate while the output is measured by a detector at the other end as shown in Fig. 2(a). Light guided in the glass substrate is assumed to decay exponentially