CONCEPTION AND REALIZATION OF A MULTIPARAMETRIC DATA ACQUISITION SYSTEM BASED ON A MICROCONTROLLER FOR GAS SENSORS

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Abstract. Real-time gas detection using a multiparameter data acquisition system has been widely adopted for many gas detection applications. It is attractive for its accurate, non-invasive, and fast determination of critical gas parameters such as concentration, temperature, and humidity. To perform real-time gas detection, data acquisition, and processing must be implemented. The aim is to simultaneously measure the responses of the gas sensor and those of humidity and temperature sensors integrated within the gas test cell to enable the evolution of relative humidity and ambient air temperature to be monitored in parallel with the gas detection process. In this work, a simple and cost-effective up to 16-channel real-time data acquisition, visualization, and storage system with a programmable voltage generator, calibrated sensors, and customized visualization software are designed and developed for gas detection applications. Experimental results show that this data acquisition system can accurately measure a wide range of sensor responses, and is suitable for measuring multiple sensors based on different materials or under different activation conditions. Dedicated software also enables users to easily capture, analyze, and save measurement data. In addition, the framework designed for a multi-parameter system is based on a real-time object-oriented methodology, enabling the implementation of hardware-software functions. The system is similar to the concept of the electronic nose, based on a network of sensors. This is one of the most viable approaches to solving the main problems encountered by most families of gas sensors, namely their lack of selectivity. By simultaneously measuring the response of sensors under different gases and environmental parameters, such as temperature, humidity, and pressure, it is possible to improve the accuracy and reliability of detection. This connection not only enables better analysis of sensor signals but also the identification of environmental influences on measurements, providing a better understanding of evaluation conditions.

Key words: Data acquisition, real-time, microcontroller, sensors, ethanol.

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1. INTRODUCTION

Real-time monitoring of gases in the air has become crucial in several areas, including industrial safety, the environment, and public health [1, 2]. The detection of hazardous gases, such as carbon monoxide (CO), carbon dioxide (CO_2), ammonia

(NH_3), and volatile organic compounds (VOCs) [16], is of paramount importance in preventing poisoning risks, monitoring pollutant emissions, and controlling industrial processes [3, 15]. When these gases are present in high concentrations or exceed regulatory thresholds, they can affect human health, cause industrial accidents, or contribute to global warming. Yet the accuracy of commercially available gas sensors is often limited by inadequate calibration and non-optimized operating conditions, compromising their effectiveness in critical applications where accurate and reliable measurements are required [4, 5].

Data acquisition systems for gas detection have developed extensively in recent years, incorporating diverse technologies to meet monitoring needs. Many existing systems use semiconductor-based electronic sensors or optical technologies to detect different gases [6]. Among the most common systems are those based on microcontrollers or Arduino platforms, which can collect and process data from gas sensors in real-time [7–9]. However, these systems have several limitations. Firstly, although commercial sensors are used widely, they are often characterized by stable resistances and are supplied with precise calibration information, such as sensor resistance and other parameters. This standardization can limit the system's flexibility when trying to characterize new or custom sensors, as these systems are often designed for a limited number of pre-established sensors (typically up to four). A particular constraint arises in applications requiring the simultaneous characterization of several sensors or sensor types.

Some more sophisticated systems incorporate optical technologies, such as infrared sensors for CO_2 or electrochemical sensors for CO. These technologies offer better accuracy but at a higher cost and often require specific equipment [10]. In addition, the calibration of these sensors is also a challenge, as they must be performed regularly to guarantee the reliability of the measurements [10–12]. Finally, integrating these systems in real-time environments poses problems of power supply stability, which can directly affect the sensitivity and repeatability of the measurements.

In our work, we utilized conductometric sensors based on metal oxides, which were custom-manufactured in our laboratory [6, 14]. These sensors offer several advantages over commercial alternatives. The ability to design and fabricate the sensors in-house provides significant flexibility, allowing them to be tailored to meet the specific requirements of the application. In addition, the fact that the fabricated sensors in the laboratory means that their electrical and chemical properties can be better controlled and adjusted to suit the particular environment where they are used. Therefore, it is essential to have a characterization system capable of adapting to any sensor manufactured, whether metal oxide sensors or other types of technology, while overcoming the limitations of current systems in terms of the number and diversity of compatible sensors. Ultimately, this highlights the importance of having a flexible and scalable system capable of characterizing a wide range of locally manufactured

sensors while overcoming the limitations of existing systems.

Our system distinguishes itself by its ability to simultaneously monitor relative humidity and ambient temperature in parallel with the gas detection process. This monitoring is essential, as these parameters directly influence the sensors' performance, particularly for MOS sensors. In addition, the design of a graphical user interface in LabVIEW enables data to be acquired, displayed, and stored in real-time. This interface facilitates system control while allowing continuous monitoring and recording of sensor data, improving the analysis of experimental results.

The acquisition system is designed around a microcontroller capable of managing several gas sensors simultaneously while optimizing sensor operating conditions, including temperature and power supply stability. Laboratory tests will validate the system's performance in controlled environments before deploying it in real-life conditions, enabling it to monitor several gases reliably and efficiently.

In conclusion, this flexible and versatile data acquisition system offers a complete solution for gas detection while enabling real-time management of ambient conditions, improving the accuracy and reliability of measurements in a diverse range of applications, from environmental monitoring to industrial safety.

2. DESIGN AND SET-UP OF GAS DETECTING SYSTEM

Figure 1 illustrates the Block diagram of multiparameter data acquisition system. Three main stages have been developed to carry out the electrical characterization of the gas sensor:

1. **Sensor activation stages:** The sensor activation process involves a thermo-activation stage, where the power supplied is controlled to regulate the temperature of the sensor's heating element. Thermo-activation is achieved by applying power to the terminals of a heating resistor integrated into the sensor. This power corresponds to a specific temperature, determined through a calibration curve. A highly precise calibration study is conducted to establish the exact relationship between the applied power and the temperature reached by the heating element. The system's temperature control ensures that the sensor's temperature remains stable and is adjusted to meet the specific requirements for gas detection. Through this thermal regulation, the system can modulate the temperature based on the chemical properties of the gases to be detected, thus enhancing the overall performance of the detection process.
2. **A measurement stage:** This stage consists of simultaneously measuring the responses of the manufactured gas sensor and those of humidity and temperature sensors integrated into the gas test cell in order to monitor changes in relative humidity and ambient air temperature in parallel with the gas detection process.

3. **Acquisition stage:** To manage the measurement, control, and data acquisition tasks, we used an ATmega 2560 microcontroller. The Table 1 below shows their various characteristics.

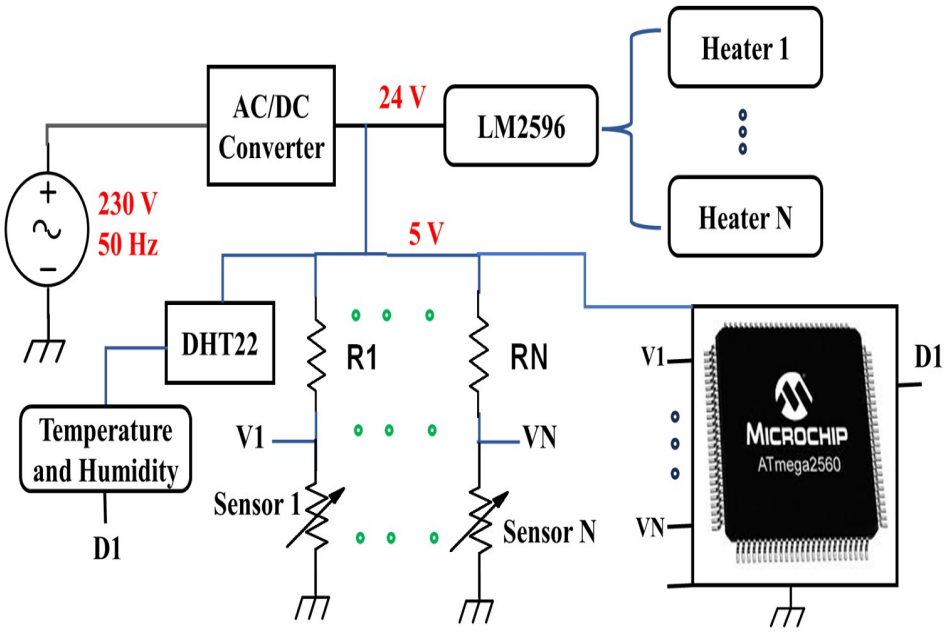


Fig. 1 – Block diagram of multiparameter data acquisition system.

Table 1

Main features of the ATmega2560 microcontroller, produced by Microchip Technology.

Characteristic	Description
Voltage	Operating voltage: 5 V
Analog Input (AI)	16
Digital I/O	54
Current	Pin I/O (5V) : 40 mA
	Pins 3,3 V : 50 mA
Clock Frequency	16 MHz
Memory	Flash memory: 256 KB
	Bootloader Flash memory: 8 KB
	SRAM: 8 KB
	EEPROM: 4 KB

2.1. DESIGN OF THE ELECTRICAL CHARACTERIZATION CIRCUITRY

2.1.1. Environmental Measurement Circuitry

Like any resistive sensor, the gas sensors we have designed can be influenced by fluctuations in environmental conditions such as humidity and temperature, so they are valuable for monitoring their evolution in the test cell.

The first stage in designing our system is to select the components sensitive to the physical phenomena we want to measure. Here is a detailed description of the sensors used:

Temperature and humidity sensor: The DHT22 is an affordable sensor that combines temperature and humidity measurement. It features a capacitive humidity sensor to measure relative humidity and a thermistor to sense ambient air temperature [17]. The collected data is sent as a digital signal *via* the data pin. The DHT22 is selected based on its technical characteristics, which we summarize in Figure 2. These characteristics guarantee high stability and reliability, even in various environmental conditions.

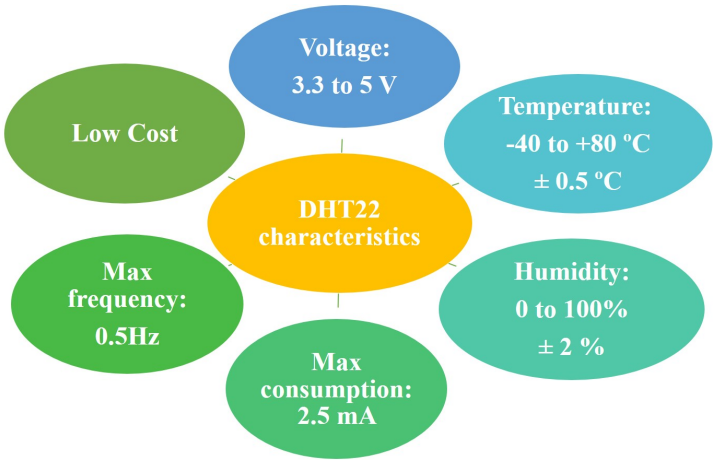


Fig. 2 – Main features of the DHT22 sensor, produced by Aosong Electronics.

2.1.2. Gas sensor conditioning circuit

For the measurement of resistance variations due to the presence of a gas, the sensors are installed in a voltage divider circuit consisting of a resistor R_L placed in series with the internal resistor R_S of the gas sensor, as shown in the electrical diagram in Figure 3.

The expression for R_S can be deduced as follows:

$$\frac{R_L}{R_L + R_S} = \frac{V_{RL}}{V_C}. \tag{1}$$

After transforming equation (1), we obtain the values of R_L and R_S according to the expressions described:

$$V_{RL} = \frac{V_C \cdot R_L}{R_L + R_S}, \tag{2}$$

$$R_S = \left(\frac{V_C}{V_{RL}} - 1\right) \cdot R_L, \tag{3}$$

where R_S is the resistance of the gas sensor, R_L is the resistance of the load, V_{RL} is the load voltage, and V_C is the supply voltage (5V).

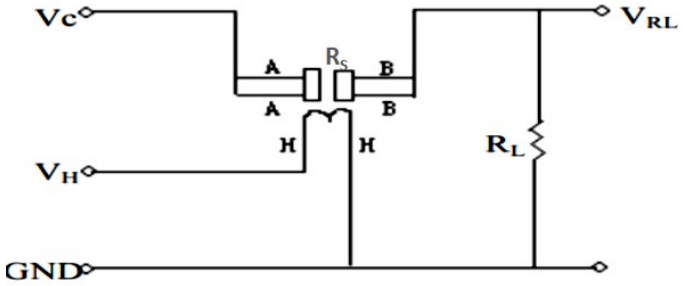


Fig. 3 – Equivalent diagram of the gas sensor conditioning circuit.

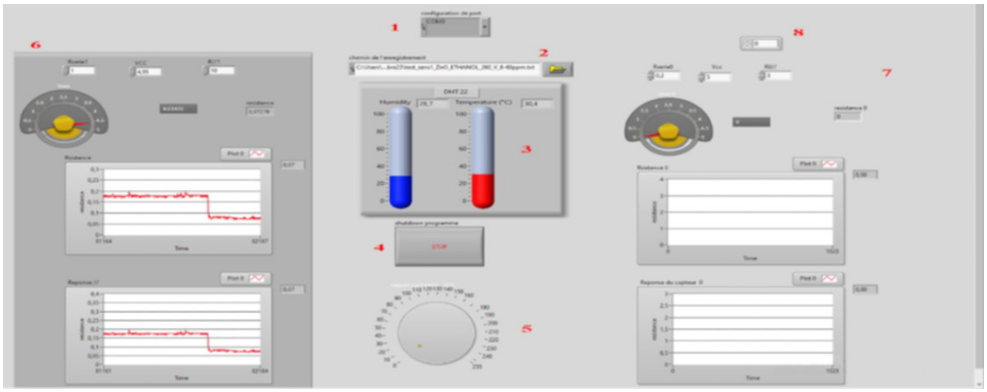
3. REAL-TIME OBJECT-ORIENTED SOFTWARE DEVELOPMENT AND PROGRAMS

After selecting the components required for the sensor's electrical characterization, we designed an acquisition interface based on the LabVIEW graphical development environment.
LabVIEW (Laboratory Virtual Instrument Engineering Workbench) is a graphical programming language used to create programs in diagram form, unlike other text-based languages. Although this is a graphic language, LabVIEW has all the classic structures of textual programming languages.

LabVIEW provides an instrumentation environment that includes the four fundamental functions required for several applications:

- Data acquisition and retrieval: instrument control (GPIB, serial, etc.), management of digital/analog input/output cards, management of image acquisition cards, etc.

- Data analysis and processing: signal processing (generation, filtering, FFT, etc.), statistical processing (regression, smoothing, averaging, etc.).
- Data presentation and storage: display (curves, 2D graphs, etc.), data storage (archiving, printing).
- Data export: data exchange (Active X, etc.), network management (TCP/IP, Internet, serial, etc.).



1 - *Port configuration block for communication of LabVIEW with Arduino*
2 - *Path to the location where data will be stored*
3 - *Temperature and humidity monitoring block in the test cell*
4 - *Program stop*
5 - *LED brightness control block*
6 - *Block for monitoring the temporal evolution of the resistance of sensor number 1*
7 - *Block for monitoring the temporal evolution of the resistance of sensor number 2*
8 - *Sensor numbering control port to display*

Fig. 4 – Developed LabVIEW interface for sensor network response acquisition.

For our proposed system, we used three fundamental functions: data acquisition, data presentation, and data storage, to develop a program to control the experimental device. The image of the interface of the program designed and developed is illustrated in Figure 4.

This interface is designed to display the responses from multiple sensors simultaneously, offering a comprehensive real-time monitoring solution. It provides the flexibility to control the number of sensors being monitored based on specific application requirements, ensuring that the system can be tailored to various experimental setups. Users can configure the interface to connect and manage the exact number of

sensors needed for their particular application, whether it is a small-scale experiment with just a few sensors or a large-scale setup involving numerous sensors.

One of the key features of this interface is its capability to display data from up to 16 sensors at the same time. This high capacity for simultaneous sensor display makes it an efficient tool for monitoring complex systems where multiple parameters need to be tracked concurrently. The interface ensures that all relevant data is presented clearly and cohesively, allowing users to quickly assess the status and performance of each sensor.

Furthermore, the interface is designed with user-friendly features that facilitate easy interpretation of the collected data. The graphical presentation of sensor responses enables quick identification of trends and anomalies, aiding in timely decision-making. By providing a centralized platform for data acquisition, visualization, and control, this interface significantly enhances the efficiency and effectiveness of the experimental process.

An additional advantage of our system is its ability to monitor environmental conditions inside the gas test cell, such as temperature and humidity. This feature is crucial for ensuring the accuracy and reliability of sensor readings, as environmental factors can significantly influence sensor performance.

This interface allows the simultaneous display of responses from multiple sensors. As shown in the Figure 4, it includes two blocks controlling the temporal evolution of the sensor resistance, with the data from two sensors displayed. Additionally, a control port (labeled 8) for sensor numbering (shown in the second block labeled 7) enables the selection and control of the number of sensors to be displayed based on their number, thereby demonstrating the flexibility and capability of the interface. Our system notably allows for the display of up to 16 sensors simultaneously, representing a significant improvement over existing systems, which can display a maximum of only four sensors. This increased capacity, coupled with the ability to monitor environmental conditions, greatly expands the applicability of this interface for more complex and demanding experimental scenarios.

3.1. SENSOR FABRICATION PROCESS

To test the proposed system performance, a gas sensor was fabricated using ZnO nanorods synthesized by the automated SILAR method [13] as a sensitive thin film. These nanorods were grown using optimized SILAR protocol and parameters, as described in [6, 14]. The surface of the well-aligned nanorods formed was analyzed thoroughly using the Image J software, and the results demonstrated an average diameter of around 176 nm [14].

4. EXPLORATION AND VALIDATION OF EXPERIMENTAL PERFORMANCE

For the exploration of gas characterization, we have designed and developed a calibration bench in our laboratory consisting of two main parts (Figures 5 and 6), namely:

1. **Gas circuitry:** This is essentially composed of the equipment for pure air generation, a mass flow controller (MFC) for controlling its flow rate, and finally, the gas circuitry (tubes, valves, etc.) for delivering the air to the test chamber.
2. **Test chamber:** a sealed cell into which the gas sample undergoing analysis is injected. The chamber contains a clean air inlet and outlet and a fan. It houses the gas sensor to be studied, with a temperature and humidity sensor for monitoring these changes in the measurement cell (Figure 6).

   The sensor response is activated in thermal mode by a heating resistor that enables it to operate at temperatures ranging from ambient to 400°C. The sensor's gas test cycle passes through 3 essential stages. During these three stages, the airflow in the cell is kept stable at 50 sccm using the mass flow controller (MFC), and the sensor resistance is measured simultaneously using the acquisition system:

   (a) **Sensor stabilization:** The sensor is first subjected to a continuous air flow until its base resistance stabilizes.

   (b) **Target gas injection:** The target gas is injected into the test cell at a predetermined concentration. During this stage, the gas detection should cause a variation in the sensor's electrical resistance compared with its base resistance under air.

   (c) **Sensor recovery:** As clean air flows through the cell while discharging, the sensor recovers the resistance baseline progressively.

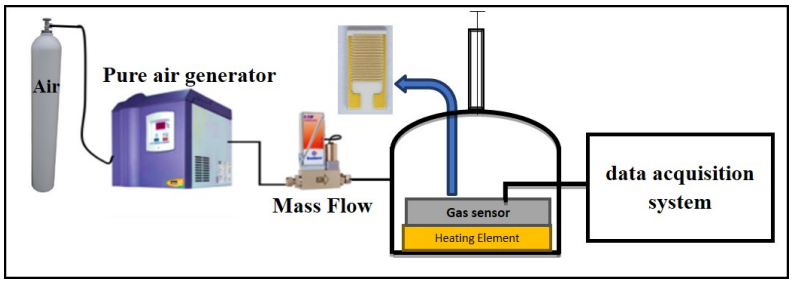


Fig. 5 – Components of gas calibration bench.

The developed system was validated by testing and exploiting the detection properties of ZnO thin films in a reducing atmosphere, namely ethanol vapor. A

1 - *Pure air generator*
2 - *5-12 V voltage generator*
3 - *5 V voltage generator*
4 - *Flow regulator*
5 - *Measurement cell*
6 - *Electrical characterization circuitry*
7 - *Computer for data acquisition and processing*

Fig. 6 – Photograph of the calibration bench used for testing gas sensor performance.

sensor was fabricated based on pure ZnO nanorods. Response curves were registered by exposing the sensors to different gas concentrations at optimum operating temperatures.

Before studying the gas detection properties of the prepared sensors, degassing steps are conducted to desorb the gases adsorbed on their surface and release the active sites. Residues of Zn (OH) and OH- groups may remain attached to the surface of the films. To eliminate these residues and any contamination due to humidity or ambient gases, the sensor is placed in the measurement chamber under a primary vacuum and then heated to 200°C for 3 hours. Once the sensor's resistance has stabilized, the testing gases are injected into the measuring cell, and resistance variations are monitored in real time. The humidity level during testing is maintained at 30%, with the temperature range between 180°C and 300°C. The ethanol gas concentrations used are 6, 12, 18, and 30 ppm.

In Figure 7(a), we evaluated the sensory capacity of the zinc oxide-based sensor.

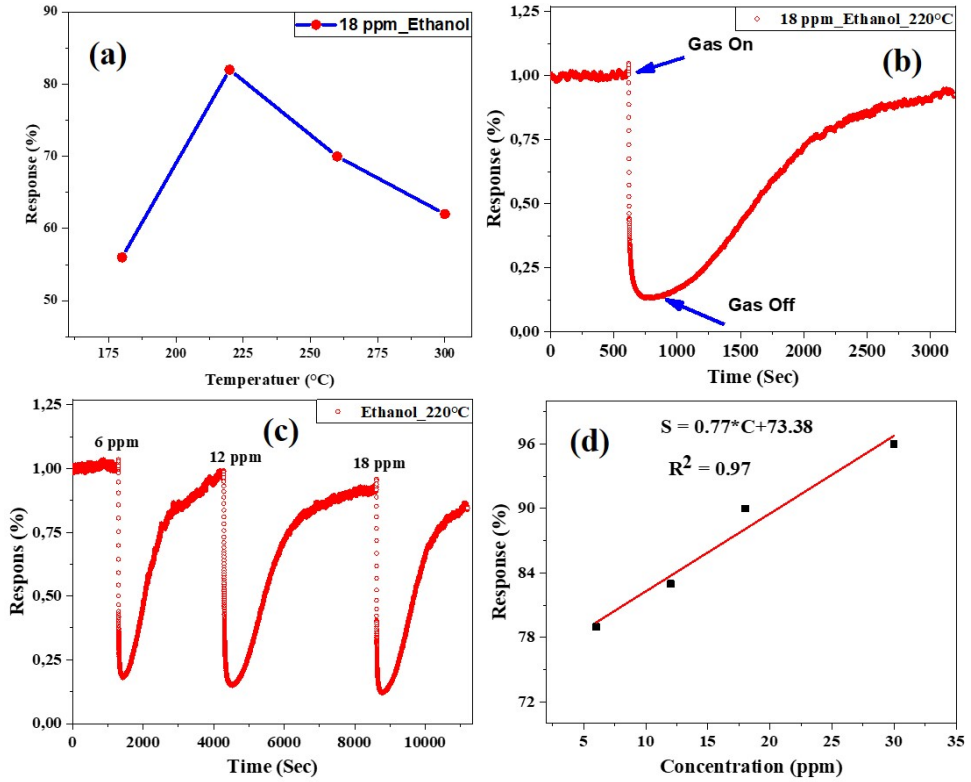


Fig. 7 – Real-time response curves recorded using a ZnO nanorod-based sensor system upon exposure to ethanol and 30% humidity: (a) response as a function of activation temperature at 18 ppm, (b) time-resistance at 18 ppm and 220°C, (c) transient dynamic responses to different ethanol concentrations, and (d) response evolution as a function of ethanol concentration at 220°C and 30% humidity.

Given the effect of activation temperature on sensor response, a study of the sensor sensitivity under a gaseous environment, *i.e.* ethanol vapor, at different activation temperatures was carried out to select the optimum temperature offering the best response under a fixed gas concentration.

Figure 7(a) shows the evolution of the response of the virgin ZnO-based sensor under ethanol vapor as a function of the activation temperature. During these tests, the vapor concentration was kept constant at 18 ppm. The optimum temperature for ethanol detection was observed to be 220°C. Under these conditions, the sensor showed a 90% response for ethanol. Figure 7(c) shows the dynamic responses of the virgin ZnO-based sensor at 220°C to different ethanol concentrations. The sensor response is manifested by a rapid drop in the sensor resistance following the injection of this compound, compared with its base resistance in the absence of the latter. After ethanol withdrawal, the sensor gradually recovers its baseline resistance as the

vapor desorbs from the surface of the sensitive layer, as can be seen in Figure 7(b). As an example, the response and recovery times displayed for the 18 ppm ethanol concentration were 13 seconds and 38 minutes respectively. As shown in Figure 7(d), the pristine ZnO-based sensor exhibits a 97% quasi linear response as a function of concentration.

5. CONCLUSION

As the sensory suitability of the various films developed had to be examined, we successfully implemented a system for the electrical characterization of multi-parameter gas sensors. This system is equipped with multimodal measurement and control circuitry, enabling the number of sensors to be characterized and the activation temperature to be customized, depending on whether the sensor is operated under thermal activation. Parameters are managed *via* a multi-channel, multi-parameter acquisition interface running under LabVIEW, enabling the response of several sensors to be visualized, controlled, and acquired simultaneously, in addition to the environmental parameters. The gas sensor was successfully fabricated by depositing the films directly onto the sensing micro-transducers, using the protocol and parameters of the automated SILAR machine. Examination of the sensory properties of the sensors under a gaseous atmosphere, namely ethanol, highlighted an interesting variability in the sensory properties of the sensors in terms of reactivity and response kinetics, depending as well on the activation temperature of the sensors.

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