

LOW COST MEASUREMENT MODULE FOR MATRIX OF AMPEROMETRIC GAS SENSOR

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Abstract – This paper describes an amperometric sensor module for gas concentration measurement. A module can be used for many types of electrochemical gas sensors without major hardware changes. Device is based on AVR ATmega8 microcontroller. As signal processing circuit a specialized integrated circuit LMP91000 configurable via I2C interface is used. The concept of a measuring system composed of several modules dedicated for a gas sensors array is presented as well. System controls modules, collects and analyses their responses. It was designed with an emphasis on universality and modularity. The proposed equipment will be used as the core of electronic nose system employed for classifying and distinguishing different levels of contamination in air.

Keywords: amperometric gas sensor, data acquisition, electronic interface, electronic nose

1. BASIC INFORMATION

In recent years, gas sensors are used in more and more applications. Gas sensors, which are commercially available or under development, have a lot of merits, such as rapid detection speed, high sensitivity and durability. What is the most important, they are very inexpensive. There are many sensor constructions working based on various concepts [1]. Gas sensors working based on amperometric principle beside semiconductor sensor are the most popular [2].

Amperometric gas sensors develop a current response signal that directly related to the concentration or partial pressure of the gaseous species [3]. An electronic device that maintains electrochemical stability in the sensor as well as buffering the current output is called a potentiostat. In the worldwide market such devices in the form of professional instruments are available (eg. Solartron Analytical 1287 electrochemical interface) usually used in stationary conditions for purposes of science. These devices usually are very sophisticated and offer excellent capabilities. However, due to a high complexity they are very expensive. There is a strong need to develop a portable and low-cost devices for measuring gas concentration with amperometric sensors.

In this paper a relatively simple and inexpensive module for measurement of gas concentration with amperometric gas sensors is proposed. Emphasis has been placed on

universality and modularity, so a few modules can be easily connected into one system for measuring response of a gas sensors matrix. The proposed equipment will be used as the core of electronic nose system employed for classifying and distinguishing different levels of contamination in air.

2. AMPEROMETRIC SENSORS

Amperometric sensor usually compose of 3-electrode electrochemical cell. It consists of a working electrode (WE), on which an electrochemical reaction takes place, a reference electrode (RE), which is used to maintain the proper potential and a counter electrode (CE), which is an inert conductor supplying the current required for electrochemical reaction at WE. A potentiostat is used to controls the potential difference between WE and RE at a desired fixed cell potential by injecting the proper amount of current into CE.

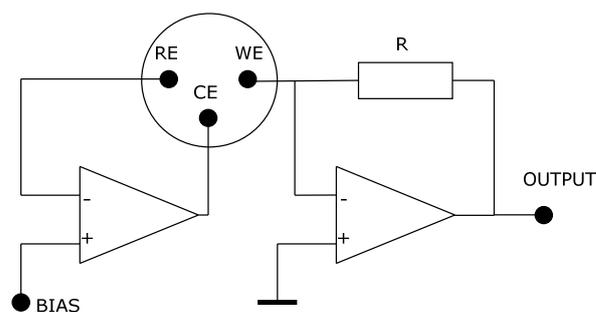


Fig. 1. A simple potentiostat circuit with amperometric sensor.

The amperometric electrochemical sensor together with an external electric circuit provides an output current signal. This current is converted to the voltage level proportional to the particular gas concentration. The current flows between the WE and CE. The WE responds to the target gas, either oxidizing or reducing the gas, creating a current flow that is proportional to the measured gas concentration. This electric current must be supplied to the sensor through the CE from the external electric circuit (Fig. 1). The potentiostat maintains a fixed potential (BIAS) at the WE with respect to the RE potential. No chemical reaction occurs on the surface

of the RE, therefore it does not affect the correct function of the sensor. As a result the sensor response is proportional only to the target gas concentration. The potential on the CE is allowed to float. The level of this potential is not important, so long as the potentiostat circuit provides sufficient voltage and current to maintain the WE at the required potential versus the RE.

Lack of selectivity is usually a common shortcoming of most of sensor available. Such sensors reacts not only for the dedicated gas but also for other gases. Various techniques for selectivity improvement can be used such as special sensor construction [4], sophisticated mode of operation [5], sensor working temperature modulation or sensor response fluctuations measurement [6, 7]. It seems that improvement of selectivity can be obtained using sensor arrays combining several sensors along with some pattern recognition algorithms as well. Extensive research based on concept of improving selectivity by combining a few not selective sensors response analysis have been done since the 80-ties of 20th century. A new type of device called an electronic nose have been proposed [8]. Thus a proposed system is designed in such way that several modules can be easily connected into one system for measuring response of amperometric gas sensors matrix.

3. AMPEROMETRIC SENSOR MODULE

A potentiostat circuit required for amperometric sensor proper operation can be designed from analogue components [9]. However, there is very attractive alternatives. The continuing progress in silicon technologies and integration levels is producing results in combing many systems on a single chip. Today, a system on chips (SoC), an integrated circuit that integrates all components of a computer or other electronic system into a single chip are becoming more common in the market. Such components may contain digital, analog or mixed-signal functions—all on a single chip substrate. This technology provides new possibilities, especially due to their low power consumption.

SoC microsystems can realize many functions. On interesting application is impedance measurement with AD5933 chip [10, 11]. Such chips not only provides possibility for miniaturized and low-power applications, but greatly simplifies system. Thus, in this paper as signal processing circuit a specialized integrated circuit LMP91000 produced by Texas Instrument is used [12]. Based on this chip a module for measurement of gas concentration based on AVR ATmega8 microcontroller is proposed.

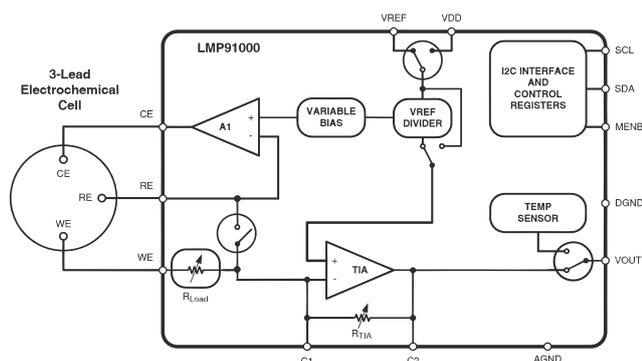


Fig. 2. LMP91000 internal structure [12].

The LMP91000 is a programmable Analog Front End for use in micro-power electrochemical sensing applications. It provides a complete signal path solution between a sensor and a microcontroller that generates an output voltage proportional to the sensor 3-electrode cell current. The LMP91000's adjustable cell bias and transimpedance amplifier gain are programmable through the I²C interface. The I²C interface can also be used for sensor diagnostics.

The internal structure of LMP91000 chip is shown in Fig. 2. LMP91000 is available since 2011, slowly becoming more commonly known and used [13, 14]. The core of the LMP91000 is a potentiostat circuit. It consists of a differential input amplifier used to compare the potential between the WE and RE to a required working bias potential (set by the Variable Bias circuitry). The error signal is amplified and applied to the CE (through the Control Amplifier- A1). Any changes in the impedance between the WE and RE will cause a change in the voltage applied to the CE, in order to maintain the constant voltage between WE and RE. A Transimpedance Amplifier connected to the WE, is used to provide an output voltage that is proportional to the cell current. The WE is held at virtual ground (Internal ground) by the transimpedance amplifier. The potentiostat will compare the reference voltage to the desired bias potential and adjust the voltage at the CE to maintain the proper working-to-reference voltage.

The transimpedance amplifier (TIA) has 7 programmable internal gain resistors. This accommodates the full scale ranges of most existing sensors. Moreover an external gain resistor can be connected to the LMP91000 between C1 and C2 pins. The gain is set through the I²C interface.

The control amplifier (A1 op amp) has two tasks: providing initial charge to the sensor and providing a bias voltage to the sensor. A1 has the capability to drive up to 10 mA into the sensor. A1 is able to sink and source current according to the connected gas sensor (reducing or oxidizing gas sensor). It can be powered down to reduce system power consumption. However powering down A1 is not recommended, as it may take a long time for the sensor to recover from this situation.

The Variable Bias block circuitry provides the amount of bias voltage required by a biased gas sensor between its RE and WE. The bias voltage can be programmed to be 1% to 24% (14 steps in total) of the supply, or of the external reference voltage. The 14 steps can be programmed through the I²C interface. The polarity of the bias can be also programmed.

The internal Zero is the voltage at the non-inverting pin of the TIA. The internal zero can be programmed to be either 67%, 50% or 20%, of the supply, or the external reference voltage. This provides both sufficient headroom for the CE of the sensor to swing, in case of sudden changes in the gas concentration, and best use of the ADC's full scale input range. The internal zero is provided through an internal voltage divider. The divider is programmed through the I²C interface.

The embedded temperature sensor is available, but not used in proposed module.

Amperometric gas sensor module based on LMP91000 have been proposed. Each module measures response of single amperometric gas sensors. Its block structure is shown in Fig. 3. ATmega8 is a heart of proposed module.

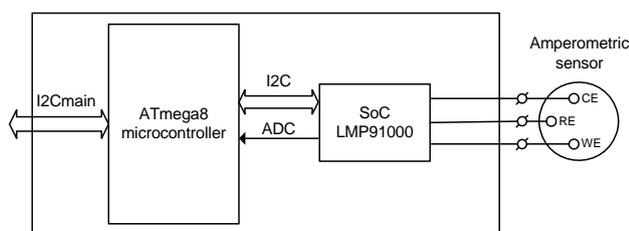


Fig. 3. Block diagram of the amperometric sensor module.

Microcontroller is responsible for communication with the rest of the system (I2Cmain). Microcontroller build in Two Wire Interface (TWI) bus, which is I2C compatible, is used. Microcontroller is acting on this bus as a SLAVE device with individually set slave address. The ATmega8 also responds to I²C General Call Address. This solution allows to connect multiple analysers to the same bus and control them separately (using address) or all at the same time (using General Call Address).

For configuration of the SoC two unused pins of microcontroller are controlled using software procedures. This way communication of ATmega8 and SoC is manually realized in MASTER mode. It is possible to configure various parameters such as: the range of the output voltage, the voltage of potentiostat circuit, gain of transimpedance amplifier, load of gas sensors and many others which are more described in datasheet for LMP91000. Generally, one set of adjustments correspond to certain type of electrochemical sensor. If it is necessary to use other type of sensor, it is possible to do it by changing the programmable parameters within the LMP91000 integrated circuits.

Last task of the module is to measure the voltage at the SoC output pin, which is proportional to the concentration of the target gas. The voltage is converted to digital format via a 10-bit ATmega8 internal analog digital converter (ADC). Software averaging was used, thus low ADC resolution did not affect the measurements accuracy.

4. ARCHITECTURE OF THE MEASUREMENT SYSTEM

The block diagram of the proposed measurement system is presented in Fig. 4. All main system components, sensors modules and supervisory module, are connected using I²C bus. I²C have been chosen due to simplicity and flexibility. Only two bus lines, namely Sda and Scl, are required. Each device connected to the bus is distinguished by a unique address. Each sensor module allows connecting one sensor.

All measured data are collected and processed by supervising module. In current system version Raspberry Pi computer with linux operating system is used for this purpose. Measured sensor response are stored in Mysql database. User control and data presentation is available through web access.

For processing artificial neural network was employed. Dedicated software was developed in order to realize all functions. This architecture provides great flexibility, because all changes, both in individual measurement modules or the central module can be made on the basis of new software upload. There is no need to make hardware changes. Preliminary test confirms system usability as an e-nose system.

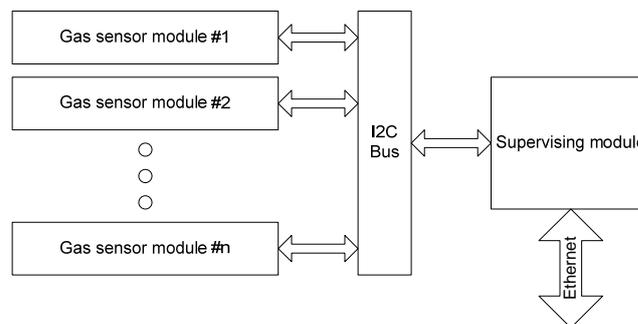


Fig. 4. Block diagram of the measurement system.

5. TEST RESULTS

A prototype of proposed amperometric sensor module was realized using NXP SC18IM700 RS232 to I²C converter, Texas Instruments LMP91000EVM and Kamami ZL2AVR evaluation boards. Dedicated software for PC and AVR microcontroller have been developed. Ammonia CiTiceL 7AM ammonia sensors was used for test [15]. This sensor have nominal range of operation 0-50 ppm SO₂ and provides output signal of 0.12±0.04μA/ppm.

Several registers control LMP91000 chip behaviour. The lock bit enables and disables the writing of the TIACN and the REFCN registers. In order to change the content of the TIACN and the REFCN registers the lock bit needs to be set to zero (LOCK - Protection Register). Then the parameters in the MODECN - Mode Control Register must be set to 3-lead amperometric cell configuration and FET shorting feature must be disabled. The measuring module was configured to work with the selected sensor (REFCN - Reference Control Register). U_{ref} voltage was set to internal (5 V). Then, the voltage V_{bias}, inflicted by the system is set to 6% of the reference voltage U_{ref}, so that the sensor is biased with a voltage of 300 mV, which is the operating voltage of the sensor. Bias sign was set to positive. Internal zero with value of 50% of reference voltage was selected. The resistance of the transimpedance amplifier is set to R_{TIA} = 120 kOhm, while resistance R_{LOAD} had the value of 100 Ω (TIACN - TIA Control Register). Then the sensor response was measured at various synthetic mixtures of air and ammonia in various mixtures.

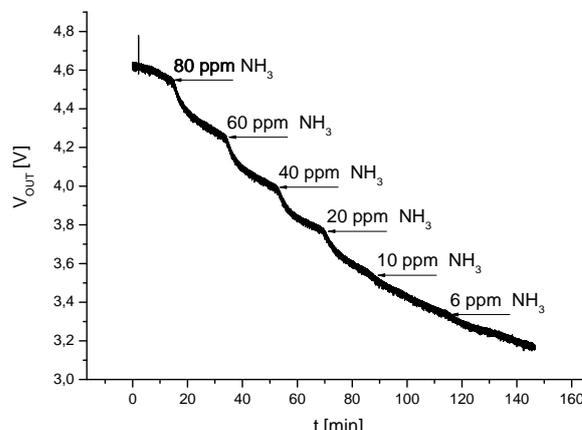


Fig. 5. Voltage response of module with 7AM CiTiceL 7AM ammonia sensor.

Continuous measurements were made of voltage V_{OUT} at the output of the module (Fig. 5). Change in the composition of the gas mixture was carried out at a period of 15 minutes. It can be seen that this time was too short and sensor response did not succeed to stabilize. Such long response time is due to the large volume of measuring cell and gas supply system.

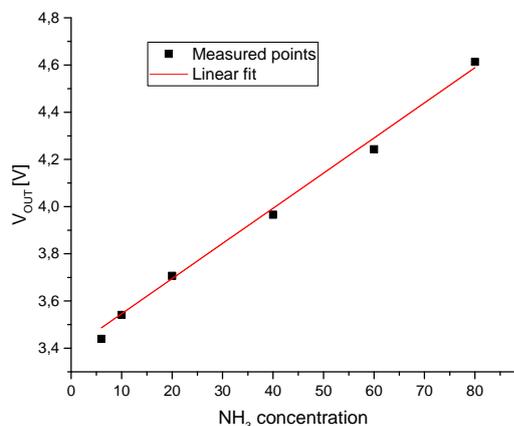


Fig. 6. Voltage response of module to different NH_3 concentration.

Marked with arrows in Fig. 5 values of output voltage related to almost stable sensor response for given NH_3 concentration are presented in Fig. 6. Obtained relationship is almost linear. Slope of the curve equals to 0.0149V/ppm. Theoretical value, based on sensor datasheet and LMP91000 setup equals 0.0144V/ppm (product of R_{TIA} 120 kOhm and sensor output signal value of 0.12 μ A/ppm).

The obtained results allow us to conclude that the work proposed in the framework of the measuring module is suitable for use with amperometric sensors.

6. CONCLUSIONS

The paper presents scalable, flexible measurement system designed for measurement of amperometric gas sensors array response. The hardware part of the system consists of a number of independent, single-board modules working in parallel. They are connected each other using I2C bus, which can be controlled by software of supervising module. Achieved flexibility and scalability as well as a low price of proposed system give fair promise of its wide usage in research and practical use with gas sensors.

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