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Versatile platform for metal oxide semiconductor gas sensors for application specific optimization of temperature cycled operation

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Introduction

The gas sensor market is constantly evolving, partly due to the still increasing interest in environmental measurements to fulfill the legislative guidelines (e.g., WHO guidelines [1]) to restrict the exposure of people to certain gases, but also in the context of IoT devices for comfort. New sensors are developed in a rapid manner, so that sensors are often replaced by newer versions within short timeframes. Designing electronics to put these rapidly developing sensors into operation is time consuming and an obstacle to fast evaluation of new sensor systems that make full use of the sensors´ capabilities.

Therefore, a hard- and software platform to control metal oxide semiconductor (MOS) gas sensors and optimize their operation for different applications is being presented. The goal was to create a hardware system that meets the compromise between easy installation of various sensors and useful functionalities for sensor signal capturing. Multiple versions of the system allow the evaluation of a variety of analog and digital sensors and to control temperature cycled operation (TCO) to increase selectivity, sensitivity, and stability [2].

The platform is discussed in the three categories electronics, firmware, and graphical user interface (GUI).

Electronics

In the electronics domain, three different systems were developed; two analog versions and a digital version. With all their peripheral components, they form either an "Analog Measurement System" or a "Digital Measurement System"

Analog Measurement System

The task of the Analog Measurement System is to retrieve information from an analog gas sensor, respectively its heater unit and its sensitive layer. Therefore, voltage over and current through the heater as well as the conductance G of the sensitive layer are to be measured.

Fig. 1 shows the block diagram for the analog system. It consists of a "Sensor Board", a "Log Board" and a measurement board.

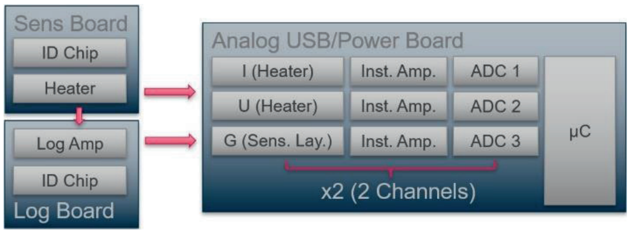

Fig. 1: Block diagram for the Analog Measurement System (represents both analog versions).

Within the system, there are two different measurement boards to be chosen:

The "Analog USB Board" is suitable for microstructured analog gas sensors with low power consumption (e.g., AS-MLV-P2 by Sciosense) and the "Analog Power Board" can be used for ceramic analog gas sensors with high power consumption (e.g., GGS-1530 by Umweltsensortechnik).

The Analog Sensor Board provides the voltage over the heater for the Analog USB/Power Board and the conductance of the sensitive layer for the Log Board. From there, the conductance is processed and forwarded to the measurement board. The three different information types are processed and delivered to the microcontroller. There are two channels of that kind which allow simultaneous operation of up to two analog sensors. From the microcontroller, the data is processed by firmware and GUI.

Analog USB Board

The Analog USB Board allows to define a temperature cycle, i.e. allows for temperature cycled operation (TCO), and controls the temperature of the sensitive layers set by the heater accordingly.

The heater is the key part of the analog measurement process. When connected to a stack of Sensor Board and Log Board, the Analog USB/Power Board is connected to the positive and negative potential of the heater. Therefore, it can access the voltage over the heater as well as the current through the heater by using a shunt (cf. Fig. 2). Voltage and current are then processed symmetrically via following instrumentation amplifiers.

Furthermore, the symmetric, conductance-related voltage from the Log Board is forwarded to an instrumentation amplifier. After amplification, the data is slightly filtered and carried on to the microcontroller or rather Teensy 4.0 [6] which is also used for the Digital Board. Therefore, the firmware can be written in a general fashion for all systems.

Analog Power Board

Compared to the Analog USB Board, the Analog Power Board only differs within the reference voltage for the DAC and the instrumentation amplifiers and necessary changes to keep the system consistent with the increased voltage and power demand (cf. Fig. 2).

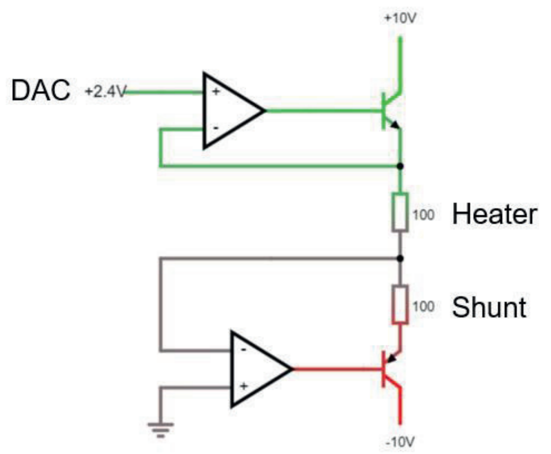

Fig. 2: Conceptional schematic for the heater voltage and current input section (power version).

While that increases the power consumption and necessary robustness of the building parts, it leads to a bigger measurement range and a higher measurement accuracy.

Analog Sensor Board

The Analog Sensor Board is designed to mount the analog sensor that is to be analyzed and it provides analog connections for the Log Board and the Analog USB/Power Board.

The Analog Sensor Board itself can be mounted and connected to the Log Board which can thereby process the output of the sensitive layer. For the measurement board, it provides pins to the positive and negative potential of the heater. Additionally, every Analog Sensor Board contains an ID chip to be identifiable by the hardware and the user.

Log Board

The Log Board performs logarithmic amplification which allows a large dynamic measurement range [7] and creates a symmetric signal for the conductance. Accordingly, the characteristic curve of the sensor is described by

$$U_{log} = 0{,}5\ \mathrm{V} \cdot \log\left(\frac{1\ \mathrm{mA} \cdot R_{sens}}{250\ \mathrm{mV}}\right).$$

The Log Board uses an USB-C port for power supply and provides analog connections to the Analog USB/Power Board. Similar to the Analog Sensor Board, every Log Board carries an ID chip. In this case, the characteristic curve shown above is also saved on the ID chip.

Digital Measurement System

The Digital Measurement System is a very flexible variant of the system because it directly retrieves digital sensor information. The standardization of digital busses (I2C, SPI) makes the incorporation and use of new digital sensors easy and efficient. Furthermore, there is no analog data processing needed which leads to a much simpler hardware system.

The Digital Measurement System does not need a Log Board, but it is also a combination of the “Digital Sensor Board” and the “Digital Board” as shown in Fig. 3:

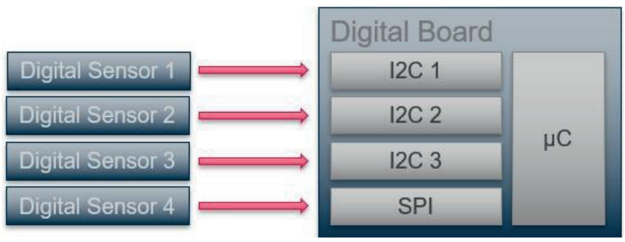

Fig. 3: Block diagram for the Digital Measurement System.

The Sensors send their measurement data directly via digital busses. Three I2C busses as well as an aditional SPI bus can be used simultaneously which allows the use of up to four digital sensors. From there, firmware and GUI take over for data processing and management.

For the Digital Measurement System, the number of operable sensors can be increased by serial concatenation of different sensors at each channel whereas the Analog Measurement System is limited to two sensors. Analog and digital in- and outputs for synchronization with other systems are available for both the Digital- and the Analog Measurement System.

Digital Sensor Boards

In this case, the Digital Sensor Board only needs to forward its digital sensor output to the Digital Board.
The Digital Sensor Board consists of the sensor itself, connectors for supply and I2C/SPI, and an opening hole for the sensor to perceive gases.
As well as the Analog Sensor Boards, it also contains an ID chip.

Digital Board

As the analog versions, the Digital Board allows TCO for digital sensors, if the firmware of the digital sensor supports this feature.
The Digital Board consists of a Teensy 4.0 and the necessary periphery to run sensors via I2C or SPI. The possibilities and constraints here are mostly derived by the firmware because, for this board, the compatibility of a sensor depends mainly on the firmware implementation. The three necessities for a sensor to be compatible with the digital board are:

1) Sends sensor data via I2C (or SPI)
2) Can be run with $\leq$ 3.3V
3) Firmware implementation is possible

The Digital Board, an example for the Analog Board and the Analog Sensor Board plugged onto a Log Board are shown in Fig. 4:

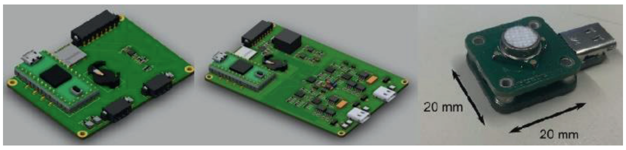

Fig. 4: Left to right: Digital Board, Analog USB Board, Analog Sensor Board on top of a Log Board.

Firmware

The firmware handles the different hardware components and assures that time relevant tasks are executed correctly without delay from any further control software. Since the different hardware versions have different levels of functionality, the firmware differs between board types. Nevertheless, there is only one source that can detect what hardware is used and compile the correct code with a user-supplied tag. This means that there is only one code for all the different hardware systems.
To make a new sensor available to the system, the communication interface needs to be implemented, and the relevant variables have to be made available to the internal registry system of the firmware. After that, these variables are automatically shown in the GUI and, depending on configuration, saved to file without further changes.
This modularity enables easy implementation of further semiconductor gas sensors and other kinds of sensors (accelerometer, pressure sensor, etc.) if the electrical specifications fit to the described hardware. Additional GPIO Pins enable the use of customizable triggers to signal events.
As soon as a sensor is connected (assuming the type of sensors has already been implemented), the firmware automatically detects the sensor type and sets it to a default configuration, predefined in the firmware. Depending on the available commands, it can be run in the mode provided by the manufacturer or in an advanced mode where the user can define sensor characteristics e.g.: hotplate temperature profiles, sample rates, and which of these values should be saved to file, etc.
The sensor configuration can either be done in the GUI or by configuration file, which is added during compilation. This makes it possible to create custom system configurations for easy distribution to clients without extensive knowledge of gas sensors operating modes or the hardware setup. Currently, the data is streamed via USB to the host device (e.g., PC, notebook, Raspberry Pi), for which the GUI is currently mandatory. In a future release the data can also be written to a SD card, but this is not implemented yet. Therefore, it is only possible to stream data via USB to any connected host device.
As mentioned above, the analog version differs from the digital one. As shown in Fig. 4 the analog version has a much larger front end which consists of analog digital converters and a heater controller for each channel. To operate as many sensors as possible with as few different hardware systems as possible, the parameters of these chips must be calibrated for each sensor type. Therefore, characteristic features of the sensor like sensor resistance range, hotplate base resistance and temperature characteristics, logarithmic amplifier gain, etc. need to be known in advance.
For temperature control, a PID feedback controller is implemented. The P, I, and D parameters also need to be known for each sensor type to ensure correct operation because they heavily rely on the sensor and hotplate size, position, and package assembly. Fortunately, all parameters needed for operation of

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already implemented sensors are stored on the ID chip of each sensor board and will be read automatically during the connection process. Thus, the system sets itself up for the connected analog sensors automatically. For new sensors, this has to be done once and saved to the ID chip during assembly of the sensor chips.
To ensure the greatest possible flexibility in configuration, it is possible to select the control method of the temperature feedback controller for the heater between resistance, voltage, current or power. It is also possible to change the control method during measurements to test different control methods.

Graphical User Interface – GUI

The control software and graphical user interface “Sensor Control Center” is written in Python and identifies sensors automatically for the user by retrieving ID information from the firmware. Firmware updates can be uploaded through the GUI as well. The GUI can be mainly divided into three sections.

Hardware Settings and Readout Section

The hardware settings and readout section of the GUI lists all sensors connected to a channel of the chosen digital board or analog USB board. All hardware systems can independently be parametrized which is handled by an internal tree structure. Each sensors resistance, heater setpoint, and temperature feedback is registered and live updated as well as the alterable sample rate of the board. Additionally, analog devices also list their alterable PID Controller settings. An example for a list of hardware settings is shown in Fig. 5:

Fig. 5: Hardware Settings and Readout Section: Parameters and states of the connected hardware.

Sequence Section

The sequence section enables the design of temperature cycles for each listed sensor or individual hotplate. The established temperature cycle will also be displayed in a plot area as shown in Fig. 6:

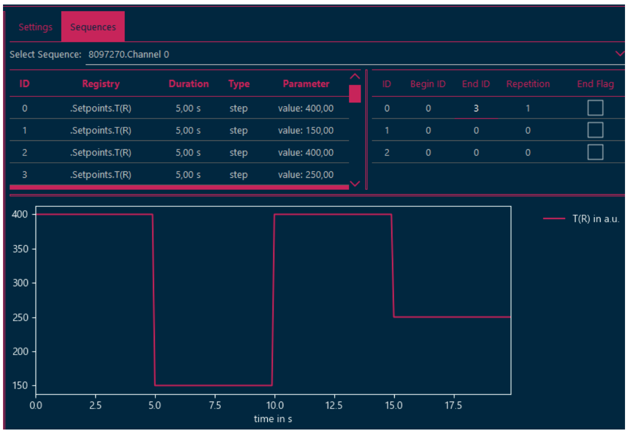

Fig. 6: Sequence section: Design of a temperature cycle as displayed by the GUI.

Measurement Section

The measurement section provides writable fields to safe meta information regarding the measurement like filename, user, E-Mail, project, and a general comment field. In a last step, the measurement length and a memory location can be assigned before the start of the measurement. Running measurements can be monitored with a live updated table and adjustable time intervals of the measurements are saved in the Hierarchical Data Format (HDF5).

Results

With the described sensor patforms, a variety of sensors can be used. Some notable examples of already incorporated sensors are listed here for the different board types:
Analog USB Board:

- Sciosense AS-MLV
- Sciosense AS-MLV-P2
- Sciosense CCS 801
- Figaro TGS 8100

Analog Power Board:

- Umweltsensortechnik GGS all types

Digital Board:

- Sensirion SHT 35
- Sensirion SGP 30/40 (cf. fig. 7)
- Sensirion SCD 41
- Bosch BME 280/680/688 (cf. fig. 7)
- Renesas ZMOD 4410/4450/4510 (cf. fig. 7)

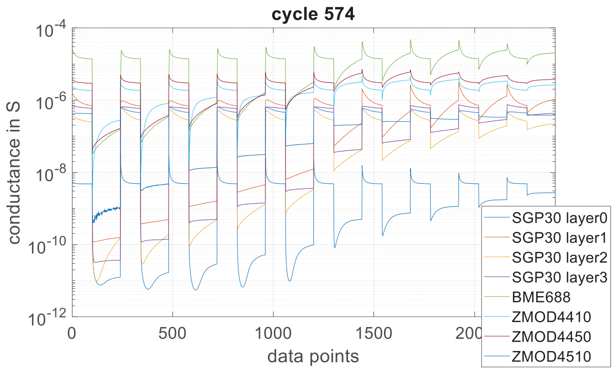

Fig. 7: Conductance of the gas sensitive layers in a temperature cycle with the Sensirion SGP30, Bosch BME688, Renesas ZMOD connected to the same system.

The system was already used to perform publicized measurement campaigns for measuring indoor air quality as a whole and characteristic VOCs selectively with a variety of gas sensors. This is only possible with a modular extendable system which can perform temperature cycled operation reliable [3], [4] and [5].

Additionally, an example of one temperature cycle with different sensors is shown in Fig. 7. The sensors are all sampled with the same sample rate of 20 Hz per sensitive layer. This shows the versatility of the system. The number of connectable sensors is only limited by the data throughput of the three I2C channels, which highly depends on communication overhead and sample rate.

Discussion

The measurements presented above show, that the Analog Measurement System follows high quality standards. The presented hardware enables to use the sensors on their technological limit, allowing the detection of sub-ppb concentrations of various gases in the laboratory and the detection of low ppb concentrations in complex backgrounds [3].

Additionally, the use of digital sensor systems allows an efficient and consistent usage of new sensor types.

By using three hardware versions with their unique firmware and a unified graphical user interface (GUI) with an easy to expand tree structure, a fast incorporation of new gas sensors for testing in new applications is possible. Furthermore, the developed systems enable the use of gas sensors in a broad range of applications and cover the bigger part of the gas sensor market.

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