Pulsed-temperature metal oxide gas sensors for microwatt power consumption

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ABSTRACT Metal Oxide (MOX) gas sensors rely on chemical reactions that occur efficiently at high temperatures, resulting in too-demanding power requirements for certain applications. Operating the sensor under a Pulsed-Temperature Operation (PTO), by which the sensor heater is switched ON and OFF periodically, is a common practice to reduce the power consumption. However, the sensor performance is degraded as the OFF periods become larger. Other research works studied, generally, PTO schemes applying waveforms to the heater with time periods of seconds and duty cycles above 20%. Here, instead, we explore the behaviour of PTO sensors working under aggressive schemes, reaching power savings of 99% and beyond with respect to continuous heater stimulation. Using sensor sensitivity and the limit of detection, we evaluated waveforms to the heater with time periods of seconds and duty cycles above 20%. Here, instead, we explore the behaviour of PTO sensors working under aggressive schemes, reaching power savings of 99% and beyond with respect to continuous heater stimulation. Using sensor sensitivity and the limit of detection, we evaluated four Ultra Low Power (ULP) sensors under different PTO schemes exposed to ammonia, ethylene, and acetaldehyde. Results show that it is possible to operate the sensors with total power consumption in the range of microwatts. Despite the aggressive power reduction, sensor sensitivity suffers only a moderate decline and the limit of detection may degrade up to a factor five. This is, however, gas-dependent and should be explored on a case-by-case basis since, for example, the same degradation has not been observed for ammonia. Finally, the run-in time, i.e., the time required to get a stable response immediately after switching on the sensor, increases when reducing the power consumption, from 10 minutes to values in the range of 10-20 hours for power consumptions smaller than 200 microwatts.

INDEX TERMS Electronic nose, gas sensors, low-power operation, machine olfaction, pulsed-temperature operation, temperature modulation.

I. INTRODUCTION

Metal Oxide (MOX) gas sensors have been successfully proposed for a large diversity of applications due to its low-cost, easy operation, fast response, and sensitivity compared to other sensing technologies [1]. Furthermore, in the upcoming era of connected devices and IoT, one can expect that cost-efficient sensing devices will still encounter a new pool of applications. In fact, recent developments integrate miniaturized MOX sensors with digital and analog electronics on a single chip [2], [3] However, MOX sensors rely on
chemical reactions that occur at high temperatures. Hence, built-in heaters are integrated to bring the sensing layer to temperatures where such chemical reactions happen more efficiently. As a result, the power consumption of MOX sensors can be a limiting factor for its integration with other low-power, long-lasting autonomous systems. Improvements in sensor thermal isolation due to micromachining techniques have largely decreased the power consumption up to a few tens of mW [4].

However, in many applications even lower power consumption is desired, particularly for battery-operated systems. For example, recent mobile platforms integrated MOX gas sensors to patrol hazardous environments for gas leak detection [5], [6]. These platforms operated the gas sensors at a constant temperature, and the power consumption of each sensor was in the order of magnitude of 100 mW. Given that several MOX sensors were operated simultaneously, the power drained in the sensors may limit the total power dedicated to the motion system and reduce significantly the autonomy of the robot. Very recently, a mobile platform with three MOX sensors reduced power consumption to 35 mW per MOX sensor [7]. The requirement of bulky and expensive batteries may be a limiting factor for MOX sensors to be integrated into smaller robot platforms, such as gas-sensitive nano-drones [8]. Moreover, the use of low-power devices is a strong requirement for certain applications. For example, in food-logistics applications, where the system needs to monitor food quality during several days and batteries need to be small and flexible to fit with the shape of the package [9].

To extend the time range of the system, MOX gas sensors are typically operated under Pulsed Temperature Operation (PTO) schemes [10]–[15]. In the simplest PTO operation, the sensor heater is switched ON and OFF periodically, and the ratio between the length of the ON period and the total cycle duration (i.e., the duty-cycle) is inversely proportional to the amount of power saved. When this strategy was applied to a wearable personal exposure monitor, the device autonomy amount of power saved. When this strategy was applied to a wearable personal exposure monitor, the device autonomy

investigated three characteristic points of the response, namely the minimal resistance ($R_{\text{min}}$) occurring just after the beginning of the heating; the maximal resistance ($R_{\text{max}}$); and the steady-state resistance ($R_{\text{end}}$). Presenting CO at different concentration levels, in the range of 0-10 ppm, and using PTO schemes with different duty cycle, $D=(30, 50, 70, 90)\%$, and period, $T=(0.5, 1, 2, 5)\,$s, authors explored the sensor (MiCS-5525, SGX Sensortech) performance for different operation schemes. Interestingly, they found that the sensitivity and the optimum $D$ and $T$ values change for the different extracted features. Rossi et al. explored other features for MOX sensors under PTO modes. In particular, they showed that the discrete cosine transform (DCT) applied to the gas sensor response can produce useful gas concentration information in the first 500 ms of the heating period, instead of the 5 s required to reach a steady-state value [16].

Only a few authors proposed other features for MOX sensors under PTO schemes with shorter duty cycles, showing that MOX sensors are still sensitive to the volatile of interest under more restrictive power conditions. For example, Bicelli et al. proposed two features to characterize the sensor response after a burst of heating pulses with $D=1.4\%$ and $T=1\,$s in a TGS 2442 (Figaro Inc.) sensor [17]. Both features are computed as the differential resistance in the quasi-stable period that lasts from $t=3\,$s to $t=6\,$s after the heating pulse, divided by the differential resistance in the sensor transient ($t=2-3\,$s) or in the decay transient ($t=6-9\,$s), respectively. They found a high correlation between these two features and the CO concentration (only for CO<30 ppm) and low sensitivity to variations in ambient temperature. Macías et al. compared the output of a PTO sensor with a sensor that was powered continuously for stability reference, when both sensors were exposed to the same analyte in a gas chamber [18]. Results showed that after a linear regression, the output of the continuously powered sensor can be predicted from the output signal of the PTO sensor, enabling thereby low power operation and fast measurement time.

Nevertheless, most of the research studies explore PTO schemes applying waveforms to the heater with a time period in the range of seconds and, generally, duty cycles above 20%. Studies that use more restrictive PTO schemes do not show the sensor performance degradation as power-saving is increased. Here, instead, we propose a methodology to characterize the PTO sensors working under aggressive schemes. We employ our methodology to MOX sensors working under ultra-low power consumption (in the range of $\mu$W), reaching power savings of 99% and beyond, with respect to continuous heater stimulation. We evaluate the performance of the MOX sensors under different power conditions using two figures of merit that are suited to select the most appropriate PTO scheme.

II. MATERIALS AND METHODS

We used an array of four Ultra Low Power (ULP) gas sensors to evaluate the behaviour of the sensors under different Pulsed Temperature Operation (PTO) schemes. The conductance of...
each sensor was acquired while the sensors were exposed to different gas concentration levels of ethylene, acetaldehyde, and ammonia.

A. ULTRA LOW POWER GAS SENSORS

The different PTO schemes were tested using a customized standalone multipurpose system that integrated four ULP MOX sensors with an RFID tag. The developed multi-sensor system incorporated the RFID tag (97 x 54 mm²) along with all the necessary electronics for RF communication, sensor control and signal acquisition, including a MSP430F1611 microprocessor, 1MB flash memory (24AA1025, Microchip Corporation), RFID antenna, CPLD logic interface, and sensor signal conditioning circuits [19]. The four sensors were embedded in a TO-8 housing directly attached to the same substrate. Fig. 1 shows the RFID tag with the integrated ULP sensors. Hence, the developed compact device is well suited for the evaluation of MOX sensors working in portable units with all the required components for its operation. Moreover, to power the system, we selected a 440 µm thick, flexible battery to fulfill the demanding requirements of food logistics (Varta LPF 25) with a total capacity of 25 mAh.

Specifically, we used sensors fabricated in the Institute for Microelectronics and Microsystems, Italy. The sensing layer of the sensors was Au-doped SnO₂ for three of the sensors, and SnO₂ for the other integrated sensor. Four independent micro-hotplates with 80 µm diameter circular active area were etched in a 1.0 x 1.5 x 0.3 mm³ silicon die (see Fig. 1) [20]. The operating temperature of the sensing layer, which determines the sensor behaviour, was controlled by means of the integrated built-in heaters. A constant 1.61 V applied on the sensor heaters induced an operating temperature of 400 °C. Under these operating conditions, the sensors showed a thermal time constant of 1.5 ms and the corresponding power consumption of each heater is 14.5 mW (each heater required 9mA). As a result, a 25 mAh battery can only supply the required power to the set of four sensors for 40 minutes (2.7 hours if only one sensor is heated). More details on the sensor development and sensor characterization can be found elsewhere [4].

The operating temperature of the sensors can be controlled by a Pulse Width Modulation (PWM) signal that operates at 30 KHz, with pulses of 1.8V. At the specified frequency, the sensor thermal response behaves as a low pass filter and the operating temperature can be considered constant and equivalent to the total applied power. Four independent voltage dividers with 330 kΩ load resistors are integrated for sensor signal acquisition. With this selection, the maximum sensitivity of the system is in the range of 90kΩ and 8MΩ, which fits with the range of interest of the sensor response (between 100kΩ and 1.5MΩ). Each voltage divider was followed by a unity gain, 40 Hz cut-off frequency analogue filter to reduce noise. The filtered signals were acquired with a 12-bit ADC sampling at 330 KHz. The captured values were saved in the internal memory of the RFID tag.

FIGURE 1. Four ULP MOX gas sensors were integrated into an RFID tag with all the required electronics for sensor control and sensor signal acquisition. Adapted from [21].

B. EXPERIMENTAL SETUP

A control and acquisition system was designed to operate the sensors under the selected conditions and read the conductivity of the four sensors. The system relies on a 4-channel multiplexer (ADG704, Analog Devices), with low ON-resistance (below 8Ω) and low power consumption (0.01µW). By means of a commercial reader (TRF7960 EVM), the values stored in the RFID tag were transferred to a host PC for further data acquisition.

A computer-controlled gas delivery system was used to present different gas conditions to the gas sensor array. The gas delivery system was based on a set of Bronkhorst Mass Flow Controllers (MFC) and a fluidic system with two active branches to control the concentration and humidity levels of the sample under test. The first fluidic branch was connected to a pressurized cylinder with synthetic air (Air premier, with 20.9% ± 1% of oxygen in Nitrogen, at 99.995% purity). The second branch was used to introduce volatiles of interest to the gas mixture. In particular, we used pressured cylinders with acetaldehyde, ammonia, or ethylene. All the volatiles came at a concentration of 1 %, in a mixture of 20.9 % of oxygen and 78.1 % of nitrogen. Using the setup described above, we exposed the sensors to eight different gas concentration levels for each gas, evenly interleaved at a logarithmic scale (see Table I).

C. EXPERIMENTAL PROTOCOL

We defined an experimental protocol to study the behavior of the sensors under different PTO schemes. The PTO conditions were defined by the time during which power was applied to the sensor heaters (T_on) and the time interval until the power was applied again (T_off). The power was applied sequentially to the four heaters to operate the sensors under the specified PTO scheme (see Fig. 2). Table II shows the PTO schemes that were studied, with the corresponding power consumption
and the power savings. One can assume that the sensor operating temperature is 400 °C during the Ton time due to the fast thermal response (1.5 ms [4]), even for the shortest Ton mode (32 ms). The power savings are calculated with respect to continuous operation of the sensor (14.5 mW). Note that the PTO schemes were defined such that Toff increased while Ton was set constant (modes 1-4), or such that Ton decreased while Toff remained the same (modes 4-8). This allowed exploring the effect of Ton and Toff individually. Two additional modes in which Ton and Toff changed simultaneously were also included.

### TABLE I

**VOLATILES AND CONCENTRATION LEVELS PRESENTED TO THE SENSORS**

<table>
<thead>
<tr>
<th>Volatile</th>
<th>Acetaldehyde (ppm)</th>
<th>Ethylene (ppm)</th>
<th>Ammonia (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acetaldehyde</td>
<td>2</td>
<td>3</td>
<td>9</td>
</tr>
<tr>
<td>Ethylene</td>
<td>3</td>
<td>5</td>
<td>14</td>
</tr>
<tr>
<td>Ammonia</td>
<td>2</td>
<td>14</td>
<td>14</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>5</td>
<td>9</td>
</tr>
<tr>
<td>3</td>
<td>7</td>
<td>24</td>
<td>14</td>
</tr>
<tr>
<td>9</td>
<td>14</td>
<td>43</td>
<td>23</td>
</tr>
<tr>
<td>23</td>
<td>131</td>
<td>229</td>
<td>37</td>
</tr>
<tr>
<td>37</td>
<td>229</td>
<td>400</td>
<td>37</td>
</tr>
</tbody>
</table>

Several experiments were performed to capture the sensor behavior under the different PTO schemes. The total duration of each experiment was 11.5 hours, distributed in 40-minute segments of synthetic air exposure followed by 40-minute segments of gas presentation. Each experiment included 8 gas presentation segments, in which one target gas was presented. The concentration level was changed for the 8 segments of the same experiment to cover all the concentrations specified in Table I. The PTO mode was set and remained the same for the whole duration of each experiment. In total, 90 experiments were performed, for the 10 PTO modes, 3 target gases, and 3 repetitions of each scenario. Moreover, synthetic air was forced to flow through the delivery system every time the target gas or the PTO scheme were changed. This ensured the stabilization of the sensor to the new PTO scheme and the cleaning of the fluidic system. The complete dataset was acquired in a time period of 3 months.

### TABLE II

**OPERATION MODES APPLIED TO THE SENSORS.**

<table>
<thead>
<tr>
<th>T_on / T_off (s/s)</th>
<th>Power consumption (μW)</th>
<th>Power saving (%)</th>
<th>Battery life (days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2/20</td>
<td>1450</td>
<td>91</td>
<td>1.3</td>
</tr>
<tr>
<td>2/40</td>
<td>725</td>
<td>95.2</td>
<td>2.4</td>
</tr>
<tr>
<td>2/80</td>
<td>362.5</td>
<td>97.6</td>
<td>4.6</td>
</tr>
<tr>
<td>2/120</td>
<td>241.7</td>
<td>98.4</td>
<td>6.7</td>
</tr>
<tr>
<td>1/120</td>
<td>120.8</td>
<td>99.2</td>
<td>13</td>
</tr>
<tr>
<td>0.5/120</td>
<td>60.4</td>
<td>99.6</td>
<td>23</td>
</tr>
<tr>
<td>0.25/120</td>
<td>30.2</td>
<td>99.8</td>
<td>39</td>
</tr>
<tr>
<td>0.125/120</td>
<td>15.1</td>
<td>99.90</td>
<td>61</td>
</tr>
<tr>
<td>0.065/75</td>
<td>12.6</td>
<td>99.91</td>
<td>84</td>
</tr>
<tr>
<td>0.0325/69</td>
<td>6.8</td>
<td>99.95</td>
<td>103</td>
</tr>
</tbody>
</table>

Power consumption and power savings are calculated with respect to a continuous sensor operation. Battery life is estimated using a 25mAh battery.

III. RESULTS

A. RUN-IN TIME AND NOISE

MOX sensors require some time to exhibit stable behavior after the operation scheme is changed. We studied the time to reach a stable sensor conductivity when the sensor was heated up after being unpowered for several days. In particular, we estimated the stabilization time of the sensors for different PTO schemes assuming a first-order sensor response. We used the experiments with synthetic air to acquire the sensor responses and fit an exponential function:

$$y = Ae^{-\frac{t}{\tau}} + y_0$$

where $\tau$ is the constant time of the function. We considered $5\tau$ as the stabilization time, which corresponds to 99.3% of the steady-state response. Fig. 3 shows an example of the sensor behavior when power is applied to the heater, for different PTO schemes, with different T_on and T_off values. One can observe the dynamics of the sensor response, with an exponential decay in time until the acquired sensor signal reaches the steady-state. More power-demanding schemes reach steady-state values faster than power-saving PTO modes.

Figure 4 shows the obtained stabilization times for the different PTO schemes and sensor types. Sensors reach faster stable behavior for PTO modes with higher power consumption. In particular, the stabilization time changes dramatically, from values over 10 hours for low-consumption schemes, to several minutes for higher demanding PTO schemes. Finally, although the general behavior of the four sensors is the same, the SnO2 sensor seems to reach stabilization faster than SnO2+Au sensors in the region of higher power consumption.

To provide a closer look at the stabilization time, we built a 2-dimension map that shows the stabilization times as a function of T_on and the total cycle duration (see Fig. 5). First,
one can observe that, at constant $T_{on}$, stabilization time increases significantly for larger $T_{off}$. When $T_{on}$ is set to 2s, and $T_{off}$ ranges from 20 s to 120 s, stabilization time increases two orders of magnitude. On the other hand, when $T_{off}$ is set constant at 120 s, and $T_{on}$ is reduced from 2 s to 125 ms, stabilization time increases at a moderate rate, being about a factor of two for the four sensors. Therefore, the time during which the sensor is unpowered, $T_{off}$, seems more critical than $T_{on}$ for rapid stabilization of the sensor response. Nevertheless, larger $T_{off}$ times and shorter $T_{on}$ times result in larger sensor stabilization times.

Finally, noise can be estimated from the steady-state portion of the signals for the different PTO modes (see Fig. 3). Table 3 shows the tabulated RMSE value for each mode in the steady-state region. One can observe that the noise power increases with the power savings. This effect is particularly noticeable for the longest $T_{off} = 120$s. Nevertheless, the limit of detection is a figure of merit that takes into account noise and sensor sensitivity, providing, therefore, meaningful information for different volatiles, in particular, in the low-concentration range.

B. SENSITIVITY

To compute the sensor sensitivity, we considered eight different data points from the acquired sensor signals. The corresponding captured sensor conductance, $\tilde{G}$, was normalized as follows:

$$\tilde{G} = \frac{G - G_0}{G_0}$$

(2)

where $G$ corresponds to the captured signal and $G_0$ represents the sensor baseline.

In particular, the portion of the signal that corresponds to $T_{on}$ was divided into eight evenly distributed intervals, giving eight different features to compute the sensor response. Fig. 6 shows the normalized sensor response to increasing ammonia concentration for the eight considered acquisition data points under 2/20 PTO operation. One can conclude that for the eight different data points one obtains a similar linear response, with
We used the well-established Clifford-Tuma equation to compute the sensor sensitivity [22], [23]. The equation has been extensively validated and it relates the sensor conductance, $G$, the sensor baseline, $G_0$, and the gas concentration, $c$, with the parameters $S$ and $\beta$:

$$G = G_0 \left(1 + S c^\beta\right)$$  \hspace{1cm} (3)

In a logarithmic representation, for large values of $c$, the equation can be simplified such that $\beta$ is the slope of a linear function [24]. Hence, $\beta$ can be viewed as the sensor sensitivity. The positive shift observed in Fig. 6 is absorbed in $S$ and $G_0$, providing similar sensor sensitivity values ($\beta$) for the eight evaluated data points. Therefore, for the sake of simplicity, we continued our study with the last data point captured in the $T_{on}$ segment.

We computed the sensor sensitivity for the different PTO schemes and volatiles. Fig. 7 shows the sensor sensitivity to ammonia, ethylene, and acetaldehyde for the different PTO modes. One can observe that PTO schemes with higher power consumption result in higher sensor sensitivity. It is worth notice that the sensors operated at the highest power saving scheme (0.0325/69) show a moderate reduction in sensitivity to any of the gases, compared to the more power-demanding modes. One can observe a positive trend in the sensitivity as the power demand increases. However, the gain on the sensor sensitivity, as more power is applied to the heater, depends on the particular gas under test. For example, PTO schemes with power consumption below 15 $\mu$W show sensitivity values in the range $0.4 < \beta < 0.5$ for acetaldehyde. PTO with lower power savings ($>30$ $\mu$W) exhibit higher sensor sensitivity values $\beta > 0.6$. Similar increasing behaviors are found for ammonia and ethylene. Only when operating the sensors with the most aggressive mode (power below 7$\mu$W), the sensitivity decreased significantly for ethylene ($\beta < 0.05$) and ammonia ($\beta < 0.3$) with respect to the second less power-demanding mode.

**C. LIMIT OF DETECTION**

It was found that the level of noise also depends on the applied PTO scheme (see for example, Fig. 3). Hence, beyond the sensor sensitivity, we also explored another figure of merit that incorporates noise to the analysis. The limit of detection (LOD) defines the smallest input that can be distinguished from noise [25]. Although new approaches have been defined to determine the LOD [26], [27][28], the classic definition of the LOD is as follows:

$$LOD = x + 3\sigma$$ \hspace{1cm} (4)

where $x$ represents the sensor signal for the null-concentration input and $\sigma$ is the corresponding standard deviation (noise level).

We computed the LOD for the sensors under different PTO schemes for the three volatiles. The noise was calculated using the standard deviation of the blank samples extracted from different experiments. The null-concentration input signal corresponds to the baseline level. The LOD is then converted to the input variable (concentration) using the inverse of the linear function calculated to determine the sensor sensitivity ($\beta$ from Eq. 3). The provided LOD value is, therefore, the lowest presented concentration level that exceeds the mentioned condition.

Table 3 summarizes the LOD found for the different PTO schemes. The LOD for acetaldehyde starts to increase quickly when the overall power consumption reaches 362 $\mu$W, and the LOD increased a factor of 3 when the power consumption is as low as 60 $\mu$W. The LOD for ethylene shows similar behavior, but the decay begins at a lower power consumption PTO scheme. The LOD remains the same for all the PTO schemes with a consumption of 30 $\mu$W or higher. On the other hand, ammonia shows a robust LOD that remains constant for all the tested PTO schemes. This is probably due to the higher sensor ammonia sensitivity and robustness to noise at lower concentration levels.

![Figure 6](image6.png)

**FIGURE 6.** Sensor response to increasing ammonia concentration level, for the different considered acquisition data points, under a 2/20 PTO scheme.

![Figure 7](image7.png)

**FIGURE 7.** Sensor sensitivity to ammonia, ethylene, and acetaldehyde for different PTO schemes. The four sensors show higher sensitivity when PTO modes with higher power consumption are applied.
VOLUME XX, 2017 9

IV. CONCLUSION
Using four MOX gas sensors we show that they can be operated under pulsed temperature schemes to reduce the total power consumption in the range of microwatts. In contrast to continuous hotplate stimulation (14.5 mW), we measured the sensor performance degradation for different PTO modes that require a total power consumption in the range from 1.5 mW down to 7 μW. In particular, we explored the sensor performance under the sensor sensitivity, the limit of detection and the run-in-time.

Regarding the sensitivity, results showed that, despite the aggressive power reduction, sensor sensitivity suffers only a moderate decline for the four tested sensors. Our tests performed with ULP sensors indicate that the sensitivity changes logarithmically with the power applied to the sensor heater. The sensor sensitivity in the PTO mode depends on several processes occurring with different time dynamics. From a physical point of view, the main limiting factor is the thermal dynamics of the hotplate. Previous characterization of the hotplate showed a thermal time constant of only 1.5 ms. Hence, one can assume that after only 5 ms the sensor has reached the steady state temperature, which is much shorter than the minimum T_{on} considered in this study (32.5 ms).

In consequence, one can consider that, for all the explored PTO modes, the sensing layer reaches the same operating temperature. The second dynamic process that controls the sensor sensitivity is related to the proper conditioning of the sensor surface involving oxygen absorption after some time at room temperature (T_{off}). When the sensor temperature increases, the ionic species on the sensor surface need some time to reach a new equilibrium. Finally, in the third process, these ionic species are involved in the reaction with the target analyte. These two chemical processes are much slower than the thermal dynamics and are the limiting factor for the sensor sensitivity. It is expected that for very short T_{on} and after a long T_{off} period, these two reactions limit the electronic exchange at the sensor surface, producing a reduced sensitivity. In the general case, the dynamics of these chemical processes is not well understood. For the particular case of carbon monoxide, Bicelli et al. have devised a model of the chemical reactions [29]. Simulations show that the chemical reactions are not able to reach the stationary state in very short temperature pulses. The optimal T_{on} duration and the exact point to get the maximum sensitivity are typically explored empirically. For chemical species that require a full stabilization of the sensor surface to produce the maximum sensor response, one can expect that very short temperature pulses will result in a decrease of sensitivity, as this study confirms.

Nevertheless, we showed that significant reductions in power consumption are possible since they only result in moderate decay in sensitivity and limit of detection. For explored PTO modes, the sensitivity, and the associated limit of detection, resulted sufficient for many applications, even if degraded from the expected isothermal operation. Previous studies compared the performance of a PTO sensor with continuous operation, even though the explored PTO modes were less ambitious. Results are gas dependent and the underlying reasons are not well understood. For instance, Elmi et al. report the behavior of the same chemical sensors used in this study under pulsed temperature operation with a duty cycle of 2% [4], [21]. The authors explore the behavior for CO, NO₂ and benzene. They found that the sensitivity for CO and NO₂ increases in PTO, but the sensitivity for benzene is greatly reduced, turning the sensor almost non-sensitive to benzene. In our work, duty cycles from 10% to 0.05% are explored for different gases, namely ammonia, ethylene and acetaldehyde. In our case, a consistent but moderate reduction in sensitivity is observed. The reported sensitivity values, beta values in the range (0.2 - 0.8) are in the same order of magnitude of the beta values observed in isothermal sensors.

See for instance Fonollosa et al., where the beta values for ethanol, CO, methane and ethylene are in the range 0.1 - 0.5 for continuous operation [30]. Similarly, sensitivities reported by commercial sensors (e.g. Figaro Engineering and FIS) show beta values in the range from 0.4 to 0.8. Consequently, we can conclude that the sensor sensitivity operated under PTO scheme remains in the same order of magnitude than a continuous temperature stimulation.

We found different behavior for the LOD for the different tested volatiles. For example, the LOD for acetaldehyde rapidly increased when applying PTO with higher power-savings. The LOD for acetaldehyde degraded a factor of 5 when the power consumption was reduced to tens of microwatts, compared to the LOD using PTO with a power consumption of 1.5 mW. On the other hand, LOD for ammonia remained constant for the wide spectrum of PTO schemes. Hence, the degradation of LOD is gas-dependent and should be explored on a case-by-case basis. Finally, the run-in time, i.e., the time required to get a stable response immediately after switching on the sensor, increases when reducing the power consumption, from 10 minutes to values in the range of 10-20 hours for power consumptions smaller than 200 microwatts. For higher power-saving schemes, the long stabilization time (up to several hours) may be a limiting factor.
factor for applications that require stable measurements in short periods of time.

Our methodology to assess the performance of MOX sensors is, therefore, suitable to benchmark to what extent one can reduce power consumption while achieving a certain sensor performance. On the one hand, the sensitivity can be used to characterize the sensor performance across the entire concentration range of operation of the device. On the other hand, if the sensors are expected to work at very low concentration levels, LOD is a more appropriate measure than the sensitivity to benchmark the PTO schemes. Hence, we suggest using the sensitivity to evaluate the performance of the sensor, unless it is expected to work at low concentration levels, in which case the LOD may provide a better characterization of the sensor behavior. By exploring these two figures of merit, the practitioner can select the most appropriate energy-saving scheme for their MOX sensors.

We showed that is possible to operate ULP MOX gas sensors such that the total power consumption reaches values in the range of microwatts. This opens a new pool of applications that are sensitive to power consumption, in particular for battery-operated devices such that nano-drones or food-logistics applications that require lightweight batteries with long autonomy.

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