A customizable, low-power, wireless, embedded sensing platform for resistive nanoscale sensors

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Abstract

Customizable, portable, battery-operated, wireless platforms for interfacing high-sensitivity nanoscale sensors are a means to improve spatiotemporal measurement coverage of physical parameters. Such a platform can enable the expansion of IoT for environmental and lifestyle applications. Here we report a platform capable of acquiring currents ranging from 1.5 nA to 7.2 µA full-scale with 20-bit resolution and variable sampling rates of up to 3.125 kSPS. In addition, it features a bipolar voltage programmable in the range of −10 V to +5 V with a 3.65 mV resolution. A Finite State Machine steers the system by executing a set of embedded functions. The FSM allows for dynamic, customized adjustments of the nanosensor bias, including elevated bias schemes for self-heating, measurement range, bandwidth, sampling rate, and measurement time intervals. Furthermore, it enables data logging on external memory (SD card) and data transmission over a Bluetooth low energy connection. The average power consumption of the platform is 64.5 mW for a measurement protocol of three samples per second, including a BLE advertisement of a 0 dBm transmission power. A state-of-the-art (SoA) application of the platform performance using a CNT nanosensor, exposed to NO2 gas concentrations from 200 ppb down to 1 ppb, has been demonstrated. Although sensor signals are measured for NO2 concentrations of 1 ppb, the 3σ limit of detection (LOD) of 23 ppb is determined (1σ: 7 ppb) in slope detection mode, including the sensor signal variations in repeated measurements. The platform’s wide current range and high versatility make it suitable for signal acquisition from resistive nanosensors such as silicon nanowires, carbon nanotubes, graphene, and other 2D materials. Along with its overall low power consumption, the proposed platform is highly suitable for various sensing applications within the context of IoT.

Introduction

Recent studies have shown that poor air quality is a significant cause of premature death. WHO estimates worldwide casualties of seven million per year1. Conventional air pollution monitoring solutions are based on gas chromatography, which leads to relatively large, heavy, and expensive equipment. In addition, such equipment is stationary; requires high installation cost and strict maintenance routines. This has led to increased demand for portable, low-power consuming, customizable gas sensing platforms2.

Air quality monitoring systems are used in heating, ventilation, air conditioning systems, air purifiers, and IoT applications. Various IoT applications were developed during the last decade for sensing physical events and transmitting sensor data via wireless communications3,4. For example, modern, portable, IoT compatible solutions4–6 have enabled air pollution monitoring on a larger scale with the potential for very high spatiotemporal coverage at only a fraction of the cost7. Such sensor technology facilitates expanded use by communities, enabling new applications and increasing data volume and access8. To compare the results with other available sensors for ambient gas monitoring9, we will refer to the regulatory requirements and exposure limits for NO2. According to the EU ambient air quality limit values set by directive 2008/50/EC for the protection of human health10, the maximum admissible NO2 hourly limit value for urban areas is set to 140 µg/m3 (corresponding to around 72 ppb) (Assuming an ambient pressure of 1 atm., µg/m3 = (ppb) · (12.187) · (M)/(273.15 + °C) where M = 46...
g/mol represents the molecular weight of NO₂), whereas
on a yearly average, the NO₂ level shall not exceed 40 μg/
m³ (corresponding to around 21 ppb). An example of field
NO₂ daily average result in Europe is presented in Fig. S1.
The United States Environmental Protection Agency
(EPA), sets the hourly limit standard to 100 ppb and the
annual average to 53 ppb. Recently, a large number of
commercial sensors can accommodate measurement intervals
recommended by the EU, e.g., MAK concentration range for NO, NH₃, CO, CO₂, NO₂, or O₂. A
comprehensive review of available sensors for ambient gas
monitoring can be found in. Energy efficiency, size, and
weight are among the most critical design parameters of
an embedded sensor platform with System-on-Chip integration. The commercial sensing solution presented in proposes a similar portable system on a PCB (60 mm × 75 mm) (see Table 1). It is based on commercial off-the-shelf sensors offering multiple gas (O₃, NO₂, CO, NH₃, VOC, H₂S, SO₂, and CH₄) sensing capabilities. Despite the broad range of gases, it requires voltages above 11 up to 24 V with a total power consumption of 2.5–6 W. The configurability of the system is performed using hardware switches. The output resolution is limited to 8 bits without local storage capabilities or wireless data transfer. Another sensing solution is presented in, offering a compact CO₂ module (30 mm × 15.6 mm × 8.6 mm) for indoor air quality monitoring. It is a single gas sensor operated at 5 V, drawing 20 mA up to 200 mA of current. The signal is updated every 5 s and it features a proprietary self-calibration algorithm. However, this system is not reprogrammable and does not offer an embedded wireless transmission. For data transfer, an I2C standard interface is available. More recent work is presented in proposes a personal wearable multi-pollutant monitoring platform based on commercial off-the-shelf gas sensors. This solution tackles the challenge of low-cost MOX sensor calibration with the help of neural networks for updating the parameters with minimal user intervention. The system integrates two sensors for O₃ and CO₂, drawing 50 mA when both sensors are operated. The system demonstrates accurate measurement results in the presence of human interferences. Another work proposes a similar monitoring system for CO, SO₂, and NO₂ temperature and pressure based on commercial sensors. The system offers 16 bits of resolution and reprogrammable software with the help of a μC. It is powered by a 3.7 V Li-Poly battery cell, consuming an average power of 150 mW including the BLE connection. The capability of reprogramming the platform is however not explored. Although it relies on embedded software, it does not use the full capabilities of building custom readout functions or involving sensor signal calibration procedures. All of the aforementioned solutions are using non-SMD or bulky electrochemical sensing elements. Nanomaterials such as nanowires, graphene, modified graphene, graphene composite, carbon nanotubes (CNTs), and metal oxide (MOx) nano-composite structures have been the subject of extensive research for sensing applications due to their low dimension and high surface-to-volume ratio. A complete H₂S sensing system based on SnO₂ nanowires and dedicated front-end electronics, data post-processing, and storage. A NO₂ gas sensor based on SWCNTs as a MEMS structure has been demonstrated in with a detection trace level from 1 to 5 ppm. Although the sensor resistance exhibits linearity on exposure to NO₂ gas concentrations from 1 ppm to 5 ppm, the detection range is higher than the EU limit of 21 parts per billion (ppb) with an averaging period of 1 year. Numerous technological challenges of nanomaterial transducers, such as device variation and ON current decrease over time as reported in, remain unknown.

This work proposes a versatile embedded system that facilitates interfacing of such nanosensors using software configurable front-end readout electronics. The system demonstrates an SoA interface to ultra-sensitive CNT nanosensors for gas sensing applications, operable within the MAK limits required by the EU standards.

**Embedded hardware**

At the core of the platform design, the ATmega2560 microcontroller (μC) is used, which features flexible timer/counters for external interruptions, a serial peripheral interface (SPI) including a serial port, and software-predefined power-saving modes. The μC offers short start-up times and low power consumption (~3 mW at 1 MHz in Active Mode). The data management is ensured by a local SD card storage connected via the SPI interface. An additional transmission (TX) module was chosen to support the wireless transmission. Most IoT solutions are based on Wi-Fi communication featuring different data protocols, with a few hundred meters of link budget, 16 Mbps TX rate but relatively high current consumption of ~300 mA. Alternatively, the long-range modem (LoRa) provides a few kbps data rate with three-kilometer link budgets for current consumption of ~120 mA. However, Bluetooth low energy (BLE) offers the best compromise between a data rate of ~Mbps and low current consumption of ~10 mA. Due to the high presence of BLE mobile devices in urban areas, this solution was preferred as the wireless form of engagement with the platform. A simplified schematic of the proposed embedded system is shown in Fig. 1a.

This platform uses a current-mode readout, a widely used technique for acquiring signals from resistive nanosensors, fabricated using silicon nanowires and CNTs. Depending on the sensor and its application, the readout interface must be compatible with current values ranging
from pA to µA. For instance, the CNT has a typical resistance of ~100 kΩ to 20 MΩ, resulting in a current from 1 µA to 5 nA (bias = 100 mV). For this purpose, the embedded platform features integrated circuits capable of acquiring such low currents by a current to digital converter (CDC) and applying a potential bias with the help of a Digital to Analog Converter (DAC) to nanosensors.

Sensor bias block (SBB)

An adjustable, reprogrammable bias is highly desirable during nanosensor operation. As illustrated in Fig. 1b, the potential bias of the sensor is software-defined and converted by a 12-bit DAC MCP492246, offering 1.25 mV resolution on each channel. The software-based solution allows for easy adjustment of measurement conditions and parameters, such as sensitivity or current baseline47,48, which can be dynamically tuned over time, and extendable towards advanced, automated calibration procedures if desired. For a single 5 V battery-operated platform, an additional negative voltage is locally generated and doubled by using two charge pumps MAX66049 connected in cascade, as presented in the bottom part of Fig. 1b. The latter allows the potential bias to be programmed in the [−10 V... +5 V] range with a 3.65 mV resolution. In Supplementary Section 1, Eq. (1), the derivation is provided.

Sensor signal acquisition (SSA)

A multichannel CDC is desirable for acquiring and digitizing the nanosensor currents. Figure 1c shows the detailed schematic of DDC1145046 time-interleaved integrators in “Convert Configuration” and “Integrate Configuration” with the timing diagram. The front-end integrators are followed by dedicated ADCs (16 or 20-bit configurable resolution) connected to the serial output interface. This solution offers true integration with a variable sampling rate and a Full Scale (FS) range programmable by two parameters: Tconv and Crange, the
integration time, and integrator capacitance. The timing of the CDC is critical for accurate operation, thereby influencing the high precision results. For this purpose, an external interruption timer integrated into the µC ensures accurate clocking of the CDC integrators. A variable sampling rate ranging from \([0.001\ldots3.125]\) kSPS has been achieved by programming the \(T_{\text{conv}}\) period in the \([2000\ldots0.64]\) ms range interval.

The \(C_{\text{range}}\) is set by a combination of three dedicated digital signals, which select one out of eight possible values formed by the CDC integrated capacitor bank of \([3, 12.5, 25, 50]\) pF\(^5^0\). The resulting CDC FS output equation is presented in Supplementary Section 1, Eq. (2). Those two CDC parameters allow the system to dynamically configure its FS current range from 1.5 nA to 7.2 μA. In addition, this solution allows daisy chain connection possibilities, thereby facilitating the data shift through multiple devices. Consequently, the control signals are shared to maintain minimal digital control overhead\(^5^0\).

An event-triggered finite state machine (FSM) operating on the µC has been realized for sensing routine automation. Each of the states and transitions presented in Fig. 2a is defined to perform a single discrete action, such as programming the bias voltage amplitude and duration, controlling the CDC configuration, storing measurements on the SD card, or transmitting the data via BLE. The state transitions of the FSM can be reconfigured with the help of a comma-separated file (CSV) stored on the SD card. The CSV file contains a customizable potential bias scheme that operates the nanosensors for a predefined time interval. The resulting current measurements are stored in a separate CSV file on the SD card. An overview of the configuration file system is shown in Fig. 2b.

**Results**

**Wireless platform characterization**

The platform was designed to accommodate a sealed test chamber with a gas inlet and outlet on the PCB (see Fig. 3a). This allows for a controlled gas exposure of nanosensors under lab conditions. A smartphone paired with the platform via BLE shows tests current signals as illustrated in Fig. 3b. The SSA and the SBB are among the most critical parts of the signal acquisition path. The platform’s FS represents the maximum input current value (common for all channels, IN1 to IN4) of the SSA and is determined by the CDC’s two \(T_{\text{conv}}\) and \(C_{\text{range}}\) programmable parameters. The FS range is presented in Fig. 3c by the corresponding level contours. The platform’s bandwidth (BW) is given by the frontend integrators of the CDC\(^5^0\). They operate as classical continuous-time integrators wherein the feedback capacitor \(C_{\text{range}}\) accumulates charge for a predefined integration time \(T_{\text{conv}}\). Their derived transfer function can be found in Supplementary Section 1, Eq. (3). To fine-tune the SSA frequency response, one can set a \(T_{\text{conv}}\) parameter as shown in Fig. 3d. Various features of the platform, such as the noise, parasitic capacitances, and leakage currents originating from the PCB tracks, socket, and ceramic package, have been evaluated. With the four channels in an “open” state, Fig. 3e shows the input-referred current \(V_{\text{bias}}\), together with the current offset. A test bias file has been used for characterizing the SBB, as illustrated in Fig. 3f, where the five \(V_{\text{bias}}\) programmed in a staircase voltage step are shown. The values and the shape are adjustable with a predefined time step using the Stimuli.CSV stored on the SD card.
NO₂ sensing using a CNT nanosensor

For the SoA demonstration of the sensing platform, we refer to a CNT device (transfer and output characteristics presented in Supplementary Fig. S2) as a resistive nanosensor, exposed to NO₂ gas. The suspended architecture and the residue-free fabrication process flow of the CNT device are detailed in ref. 51. A short description is presented in Supplementary Fig. S3. Aspects of the
general gas sensor key performance parameters are presented elsewhere. \(^3\)\(^5\)\(^6\). Measurements of the CNT nanosensor were performed at atmospheric pressure by using a customized gas mixing setup. A detailed description of the setup can be found in ref. \(^5\)\(^3\). The CNT nanosensor was exposed to NO\(_2\) gas concentrations of [0, 200, 150, 100, 50, 10, 1, 0, 0] ppb under constant dry air flow. \(^5\)\(^4\). The concentration steps were chosen to start from high to low NO\(_2\) values preceded by dry air exposure for two main reasons: first, to define a baseline of the CNT nanosensor drain current in the absence of NO\(_2\) gas, and second, to highlight the effectiveness of CNT nanosensor reset by evaluating this baseline. Experimental evaluation of the baseline concerning sensing bias voltage and reset time/energy is presented in Supplementary Figs. S4 and S5. For the current set of experiments, the FSM has been programmed to acquire consecutive samples with a temporal delay of 1/3 s in between. Denoted as \(\tau\) in ref. \(^5\)\(^5\), this sampling period has been chosen due to strong signal correlation, given by the 1/f noise, and mitigating the white noise with the LPF effect. For the same CNT devices, the influence of the observation window and the sampling frequency has been investigated in a previous work which can be found in ref. \(^5\)\(^5\). Depending on the application requirements, the sampling rate of the embedded platform can be increased up to 3.125 kSPS which offers sufficient BW for acquiring a large variety of bio-signals. \(^5\)\(^6\). The detailed sampling structure and the sampling rate power consumption overhead are presented in Supplementary Figs. S6 and S7.

The experiments in Fig. 4 present a reproducible, current response of the CNT nanosensor to NO\(_2\) exposure. For the CNT nanosensor reset, a self-heating (SH) operation was performed after each concentration of NO\(_2\) exposure. The SH effect enables an accelerated gas desorption mechanism, as observable in the top part of Fig. 4.

In this bias region, the CNT current is saturated, which induces the SH onset resulting in a negative-differential conductance behavior. \(^4\)\(^5\). The bottom part of Fig. 4 shows the sensor recovery window at an elevated bias voltage of \(V_{GS} = -7.5\) V and \(V_{DS} = 0.9\) V after each exposure sequence (experimental determination of these bias levels are presented in Supplementary Figs. S4, S5, and S8). The current samples denoted as “outlier” in Fig. 4 can be ignored since they represent CDC’s first integration cycle immediately after power-on-reset. The experimental sequence was repeated thrice at the same bias levels and NO\(_2\) gas concentrations for consistency. Significant repeatability and the effective sensor reset between the measurements data sets [\#1, \#2, \#3] (gray level) are observable in Fig. 4.

**Discussion**

**CNT nanosensor signal evaluation**

One of the widely used measures to characterize the sensing performance of a transducer is the LOD value. This performance parameter is represented by the lowest NO\(_2\) concentration for the CNT nanosensor, measured with a three-sigma (3\(\sigma\)) confidence interval. Compared to
another type of sensor response (i.e., AlphaSense\(^{57}\) response presented in Fig. S9), the signal evaluation of the current CNT device is based on the former research work\(^{55}\) of the group, which presents an extensive analysis of slope detection (SD) versus quasi-steady-state (QSS) sensing regimes. By observing the CNT nanosensor current evolution over time, three different regions within a NO\(_2\) exposure pulse are highlighted in Fig. 4. The regions are named as (i) settling time (ST) of ~20 min, (ii) SD region from five to 20 min, and (iii) QSS during the last 5 min. Langmuir isotherm model\(^{58}\) can be used to analyze the adsorption state on the CNT nanosensor surface. According to this model, the initial slope of the current response during the first 12 min of NO\(_2\) exposure is evaluated as CNT nanosensor sensing variation, including relative inaccuracy of the gas setup. Note: Each data point represents an average and the standard deviation of 60 samples acquired at fixed bias conditions common for (a) and (b). \(V_{\text{GS}} = 0.1\, \text{V} \) and \(V_{\text{DS}} = -1\, \text{V}\).

The result presented in Fig. 5b shows the data from Fig. 4 denoted as QSS, wherein the average steady-state current response during the last 5 min of the 2-h NO\(_2\) exposure is evaluated as CNT nanosensor sensing response. Using the linear fit shown in Fig. 5a, b as the device calibration curve and including the resulting error bars as being the noise of the three acquired samples, the LOD can be determined by 3\(\sigma\)-root-mean-square (RMS) noise divided by the gas response slope at low gas concentrations.

Here, the \(\text{noise}_{\text{RMS}}\) is calculated as the RMS value of the slope's standard deviation across individual current signal response samples at [10, 1, 0] ppb NO\(_2\) concentration. The shaded area of Fig. 5 illustrates the standard deviation around the average current value for all measurement data sets [1, 2, #3] at each gas concentration. Using the data and their respective fits as shown in Fig. 5a, the LOD limit values are calculated as in

\[
\text{LOD}_{\text{SD}} = 3 \cdot \frac{\text{noise}_{\text{RMS}}}{\text{slope}} = 23.4 \text{ ppb} \approx 23 \text{ ppb} \tag{1}
\]

And from Fig. 5b where the QSS sensing regime is explored

\[
\text{LOD}_{\text{QSS}} = 3 \cdot \frac{\text{noise}_{\text{RMS}}}{\text{slope}} = 51.9 \text{ ppb} \approx 52 \text{ ppb} \tag{2}
\]

Operating CNT nanosensor by pulsed SH and SD, concentrations of NO\(_2\) below 23 ppb can be resolved. It has been highlighted that the initial slope sensing based
on SD can dramatically decrease the response time, offering both better linearity and dynamic range (see: Fig. 5a). In Fig. 5b, the classical approach of SS or QSS is explored, wherein the Langmuir isotherm flattening is observable at higher gas concentrations due to the complete surface coverage. In addition, the CNT nanosensors fabricated using the ultra-clean, dry-transfer technique show a significant reduction in sensitivity to humidity. The humidity cross-sensitivity experimental result of the CNT nanosensor is presented in Supplementary Fig. S11.

**Embedded platform power consumption**

The embedded platform has been supplied by a 5 V; 2800 mAh battery, and the power consumption has been monitored during the operational states. An IDLE state was defined to switch off unnecessary peripherals and execute μC power-save mode. According to the Stimuli. CSV file, a single timer is kept operational in this state, responsible for waking the remaining peripherals according to the Stimuli.CSV file. Figure 6 showed the platform’s power consumption when three current response results in a row were acquired every second, including the IDLE state in-between. This sampling rate corresponds to the typical energy consumption of an environmental monitoring station sampling at three SPS denoted as [s#1, s#2, s#3]. A low sampling rate of three SPS is preferred in this particular application for lowering the power consumption but still being fast enough in collecting sufficient samples and achieving slope-detection within a 5-min observation window for a (3σ) LOD of ~90 ppb (as illustrated in the Supplementary Fig. S10).

In Fig. 6a, the average power consumption of 64.5 mW can be observed when the proposed platform executes the custom FSM states of Fig. 2a, and the BLE is paired in advertising mode at 0 dBm TX power. The peak power consumption of about 225 mW corresponds to the CDC acquisition and SD card data storage. In Fig. 6b, the average power consumption drops to 60 mW when the BLE is ON but not paired with a mobile device. The average power consumption values are determined not considering computing power for signal evaluation. A comparison with the theoretical power consumption for the platform’s main components can be found in the supplementary Table S1.

However, the energy efficiency of the proposed platform can be further optimized by reducing, reordering, or customizing the software-defined FSM states and states transition timing. In comparison, a commercial reference platform, e.g., Aeroqual, which uses an SM-50 O₃ measurement unit for outdoor environments, provides highly accurate ozone measurements within [0…150] ppb. However, it operates at a high minimum power consumption of 2.5 W, excluding wireless communication. The Telaire 6713 from Amphenol Advanced Sensors, a sensor measuring indoor CO₂ concentrations within [400…5000] ppb with high accuracy, suffers from a similar shortcoming. While the sensor itself is suitable for wearables due to its form factor of 30 × 15.6 mm, its average power consumption of 135 mW without sensor electronics is relatively high for a long-term battery-operated system. A recently published full system solution is the W-Air module presented in employs two MOX for O₃ and CO₂ sensors from the shelf trying to eliminate the interference of VOC emissions. At a sampling rate similar to the one presented in this work, the system in draws an average power of 150 mW, twice the value compared to the average value presented in Fig. 6. The presented work confirms the
preliminary results from\textsuperscript{55} by exploring sensing solutions with repetitive experiments and portable-embedded platforms at a fraction of total power consumption compared to lab equipment. A summary of the performance of the embedded system and the CNT nanosensor in comparison to selected gas sensing solutions is presented in Table 1.

### Conclusion

We presented the concept, realization, and performance evaluation of a portable, customizable embedded platform for nanosensor applications. The platform’s hardware can adapt to the demands of the nanosensor requirements and can measure a wide current range. In addition, our solution is fully autonomous and reconfigurable, employing a user-defined instruction set. The FSM’s embedded functions allow for setting various platform parameters, namely: the CDC integration time and capacitor bank, defining the FS and BW, DAC bias level/period (including a bipolar potential beyond the supply voltage), time intervals for SD card storage and BLE data transmission. Moreover, an additional power-saving FSM-state deactivates the µC’s internal blocks and thus reduces the average power consumption to 60 mW. The power bank can ensure up to nine days of continuous operation for the measurement protocol in this configuration. An application of the embedded platform has been demonstrated by integrating an ultra-sensitive CNT nanosensor. A reproducible CNT nanosensor response to NO\textsubscript{2} exposure was demonstrated down to 1 ppb of NO\textsubscript{2} in dry air with a 3\textit{σ} LOD as low as 23 ppb (1\textit{σ}: 7 ppb). Our customizable, compact embedded sensor platform demonstrates the unique capability of CNT nanosensor readout and enables validation of the respective annual exposure limits set by the EU. The user-defined software-based solution allows for simple addition, replacement, and reordering of FSM states, thus offering a high degree of flexibility and enabling further trade-off between functionality and energy efficiency.

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### Author contributions

Conceptualization: Stefan Nedelcu and Kishan Thodkar; CNT devices: Kishan Thodkar; Software: Stefan Nedelcu; Data curation: Kishan Thodkar; Writing—original draft preparation: Stefan Nedelcu; Writing—structure, review and editing: Kishan Thodkar and Christofer Hierold; Visualization: Stefan Nedelcu and Kishan Thodkar; Supervision: Christofer Hierold. All authors have read and agreed to the published version of the paper.

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### Table 1 Summary of performance comparison

| Specification                  | This Work | 11 | 12 | 13  | 4   |
|-------------------------------|----------|----|----|-----|-----|
| System Supply [V]             | 5        | 11 | 5  | 3.6 | 5   |
| Connectivity                  | BLE/serial | I2C/serial | I2C/UART | BLE | BLE |
| Sensor material               | CNT      | MOS | NDIR for CO\textsubscript{2} | MOX for O\textsubscript{3} and CO\textsubscript{2} | Electrochemical for NO\textsubscript{2} |
| Range [ppm]                   | 0–0.2    | 0–0.2 | 0–50,000 | 0–0.2 | 0.01–50 |
| Response time [min.]          | 12       | < 1 | < 3 | < 1 | < 1.2 |
| Resolution [ppm]              | 0.023\(a/0.052\) (3\textit{σ} LOD) | 0.001 (LDL) | +/−30 ± 3\%ss | O\textsubscript{3}:0.004,CO\textsubscript{2}/64ss | ±0.02 |
| Temp./R.H. [°C/%]             | 22 °C    | 0 to 50 °C | −10 to 60 °C | −40 to 85 °C | −30 to 60 °C |
| 0% R.H.                       | 0 to 95% R.H. | 0 to 95% R.H. | 10 to 95% R.H. | 15 to 85% R.H. |
| Area [cm\textsuperscript{2}]  | 9.5 × 6.5 | 6 × 7.5 | 0.3 × 1.5 | – | – |
| Power [mW]                    | Avg. 60 @ 3 SPS | 2500–6000 | Avg. 125 | Avg. 180 | 175 |
| Sensor(s) Detector type       | CNT      | Graphene | In\textsubscript{2}O\textsubscript{3}-rGO | SnO\textsubscript{2}-NW | Ag-S-rGO |
| Limit of detection [ppb]      | 23 (3\textit{σ})\textsuperscript{a} | 100 | 50 | 100 | 500 |
| Detection principle           | Resistive | Hall bar | FET | resistive | FET |
| Power [µW]                    | <0.025–0.5\textsuperscript{c} | – | – | 20 | – |

\textsuperscript{a}For SD mode

\textsuperscript{b}For QSS mode

\textsuperscript{c}In QSS mode @ 1 ppb and SH mode
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