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Review

Optimization of power consumption for gas sensor nodes: A survey

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ABSTRACT

The Wireless Sensor Network (WSN) technology has recently been used, rather successfully, in a huge number of monitoring applications. However, the monitoring of combustible gases with WSN stands out from typical applications where the wireless communications function is much more power hungry than the sensing one. The reason behind this "dissonance" is in using catalytic or semiconductor sensors that ensure a trade-off among the safety requirements, performance and power consumption. This work provides a survey of intrinsic power optimization techniques with a special focus on recent advances in power management, sensor fabrication, sensing circuits, and measurement procedures. The paper concludes with providing a future outlook in the area.

Contents

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1. Introduction

Almost every industrial plant has some quantity of flammable and combustible liquids stored in its facility. Most of apartments and houses in Europe exploit methane based boiler facilities to heat the living space. Such conditions would require to permanently monitor, via suitable gas sensors, the atmosphere around industrial enterprises and inside houses and, in a case of dangerous situations, to timely provide and send alarm to proper (fire, police and medical) services.

Nowadays, combustible gas could be detected using several types of sensors: catalytic/semiconductor or infrared (IR) absorption. Most combustible gas detectors available in the market are powered by grid connection (or by batteries for a limited time). However, power and data transfer cables are sometimes more expensive than detectors themselves. These are especially relevant for difficult to access areas, e.g. enterprises, underground, mountains, where it is not trivial or even impossible to deploy a power grid. It is also associated with efficient gas monitoring when the sensor nodes, in some cases, have to be deployed at various heights [1] including the mixing emission height.

The solution of combustible gas monitoring problem lies in the application of WSN paradigm that has already been used in a huge number of monitoring applications [2]. A WSN consists of a number of wireless sensor nodes which measure environmental conditions using sensors and distribute the measured data over the network to a user in a multi hop manner.

The wireless sensor nodes rely on the IEEE802.15.4 standard and ZigBee or other specification designed for low power embedded systems and transmission of tiny data packets.

Abandoning wires, obviously, imposes strict requirements to power consumption of sensor nodes. This is especially relevant to the gas WSNs where a gas sensor is the most power hungry component onboard with respect to the typical applications where radio chip plays this role. The hazardous gas concentration is typically measured by WSN using optical, catalytic or semiconductor sensors [3,4].

The optical approach is implemented using optical spectroscopic trace-gas sensor platforms [5]. These platforms use optical spectroscopy to detect and quantify numerous gas species [6]. Being highly sensitive and fast in terms of sensor response, these systems satisfy safety regulations perfectly. However, circuits of this type may consume more than 500 mW, making them unsuitable for WSN applications. Another disadvantage of optical sensors is their complicated design process and much higher cost w.r.t. the catalytic and semiconductor sensors.

Sensor nodes based on catalytic and semiconductor sensors [7,8] consume less power than the nodes with an optical gas sensor on board. At the same time they are characterized by quick response and good selectivity.

Although there has been already published a number of WSN power management surveys focusing on wireless communications [9], data sampling [10], routing [11], this work focuses on the techniques and approaches aimed at the power consumption reduction of gas sensor nodes. In particular, we focus on recent advances in hardware power management in Section 2. In Section 3 we present the gas sensors' fabrication technologies which can help to further reduce the nodes' power consumption. A lion share of energy can be saved by applying an 'efficient' sensing circuit and associated gas measurement procedure, which are discussed in Section 4 and Section 5, respectively. Finally, we provide a future outlook in Section 6 where we discuss promising directions towards increasing the long-term operation of gas sensor nodes.

Table 1
Power consumption of typical electronic components used for WSN nodes design.

Component	Model, manufacturer	Power consumption
MCU	MSP430F247, Texas Instruments	Active: 1 mW Sleep: 3 uW
MCU	ATxmega32A4, Atmel	Active: 3.3 mW Sleep: 2.1 uW
Humidity sensor	808H5V5, Sencera	1.25 mW
Temperature sensor	TMP102 Texas Instruments	33 uW
Catalytic gas sensor	NAP66A, Nemoto	360 mW
Catalytic gas sensor	MC series, Hanwei Electronics	Up to 600 mW
Semiconductor gas sensor	AD81, GE	620 mW
Semiconductor gas sensor	MQ-4 Hanwei Electronics	750 mW
Radio chip	CC2430, Texas Instruments	TX: 81 mW RX: 75 mW
Radio chip	ETRX35X, Telegesys	TX: 93 mW, RX: 75 mW

2. Power management

A wireless sensor node for the gas sensing application consists of a gas sensor, an MCU, a transceiver, and a power supply with a power management circuitry. The power management circuit provides the electronic components onboard with the supply voltage in an efficient way [8]. In fact, in contrast to typical WSN monitoring applications [2] where the radio module is the main power sink, the gas detection application requires on board power hungry sensors [3,8] to meet safety requirements [12,13] and to avoid human victims and huge pecuniary loss. To put this in context, Table 1 provides some comparative data on the power consumption of typical electronic components used in the design of WSN nodes, including processors, radio transceivers and commonly used sensors.

Indeed, the gas sensors consume much more power w.r.t. typical electronic components shown in Table 1. Typically, the WSN nodes are powered by batteries and/or super capacitors [41]. The typical capacity of a single cell of AA, C, and D types is 3000, 8000, 15000 mAh, respectively. Power supply voltage for a sensor node varies from 3 to 5 V, which requires 2–3 cells. Since there are 8760 h a year, the average discharge current for AA, C, and D cells is 0.34, 1, and 2 mA, respectively. This simple estimation and understanding that the current level of development of electronics, gas sensors and batteries does not provide an opportunity to design a wireless gas sensor node which could potentially operate autonomously for several years in continuous measurement mode.

According to international safety standards [12,13], the gas detectors must guarantee a stable operation within at least one year due to a necessary gas sensor calibration every year. Therefore, it is reasonable to calibrate the sensor and replace the batteries of the sensor node simultaneously. To guarantee even one year of autonomous operation of the sensor node is not a trivial task.

The easiest way to overcome the problem of power consumption is to put the sensor node in sleep mode for a long time. A number of standards, however, limit the maximum sleep time for gas sensing applications [1,12] which forces the research community to perform extra investigations and empirical studies to address the problem of high power consumption of gas sensor nodes.

2.1. Power management circuits

Typically, the trivial actions to reduce the power consumption include disabling the unused hardware and sub-devices in an MCU and/or a transceiver. In this section we discuss more advanced approaches.

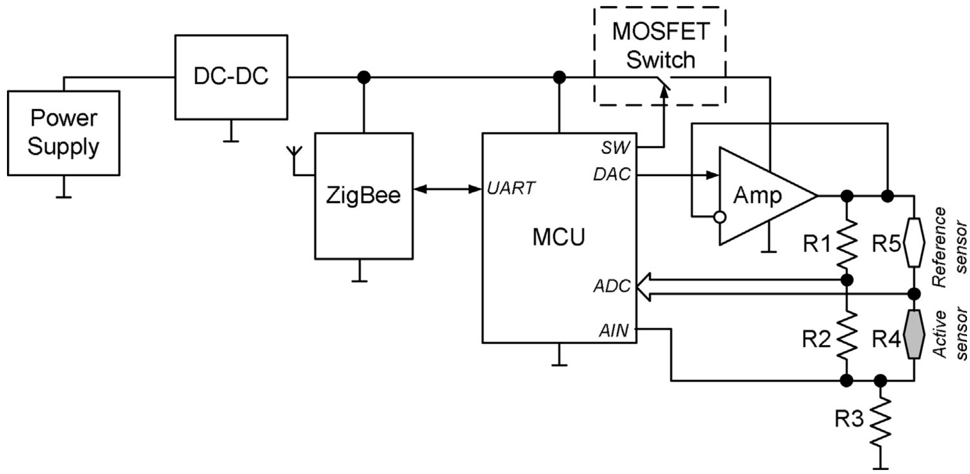

Fig. 1. Schematic diagram of the wireless gas sensor node (Data from Ref. [19]).

It is worth noting that the requirements for power supply voltage differ for the analogue and digital electronic components of a sensor node. Digital devices, for instance, an MCU and a transceiver, have a wide supply voltage range from 2.1 V to 3.6 V [14]. In this case a user can directly apply two standard non-rechargeable 1.5 V AA cells wired in series or one 3.6 V AA Li-ion cell. Without the application of the power management and voltage regulation techniques, the batteries will be practically useless when depleted up to 2.1 V. As for supplying the catalytic or semiconductor gas sensors and their associated sensing circuit, a regulated voltage is typically used to heat them up. The level of heating voltage depends on the sensor specification and measurement procedure (see Section 5).

In power management circuits for the wireless gas sensor nodes either linear regulator or DC/DC is used. The major advantages of a linear regulator are its simple circuit and low noise level. At the same time it is characterized by low efficiency due to the power dissipation (up to 25 mW during heating of a typical catalytic gas sensor) on a regulating element in its circuit. DC/DC is a switching regulator characterized by high efficiency: the series element is either on or switched off, therefore, it dissipates almost no power. To increase the efficiency of voltage conversion, a DC/DC, as well as a linear regulator, have to generate the output voltage that can be directly used to supply the gas sensors. In [15] the authors applied 2.8 V generated by a linear regulator to heat the sensors up. The same voltage level can be used to supply a digital part of the sensor node.

The power management becomes a more complicated task when a complicated heating profile is applied to the gas sensors [16,17] with the aim to reduce their power consumption. In this case the supply voltage used to heat the sensors up may vary in a wide range (from 0 to 3 V) and, therefore, can not be used for consecutive supplying of digital circuit. This problem was addressed in [18] by designing a circuit with two separate “analogue” and “digital” power supplies. The analogue power supply is composed of three 1.5 V C-sized alkaline cells and supplies the gas sensor system through a linear regulator. The digital power supply is composed of one 3.6 V AA-sized Li based cell with a nominal capacity of 2.6 Ah and powers the MCU and the transceiver. This approach prevents digital noise from entering the analogue circuit. Moreover, it ensures high reliability and long-term operation of the device because the average sensor power consumption exceeds the digital circuit consumption: in case of a discharge of the 'analogue' battery, the node does not disconnect from the WSN and can broadcast alert messages.

A built-in MCU's DAC can not provide the sufficient current of approximately 250 mA for heating the sensors directly. However, a DAC and an output amplifier can together be used to adjust the heating voltage supplied from a power supply via a DC/DC (see Fig. 1) [19]. The measurement circuit is enabled by a MOSFET switch when sensing occurs. In this case the circuit ensures negligible power dissipation.

Another option of sensors' heating and their consecutive power management is the application of Pulse-Width Modulation (PWM) [8]. PWM-based circuit does not require extra electronic components like an amplifier or DAC. In this case, the amplifier “Amp” will be crossed out from Fig. 1 and PWM is provided by the voltage across MOSFET, which comes from the output SW of the MCU. PWM-based heating pulse is generated by the MCU software and is used to control a transistor switch to pass the heating current to the sensing circuit. Using the PWM-based heating a user has the possibility of changing the average voltage by varying the length and duty cycle of pulses and provide the necessary heating profile with respect to the application requirements. The PWM approach provides the additional reduction of power consumption due to reduction of the average heating voltage. In fact, the PWM-based sensor heating can lead to the sensor damage due to frequent switching on/off of heating voltage.

2.2. *Energy harvesting*

The problem of providing independent power supply for all devices in WSN including sensor nodes, coordinators and actuators is a problem of top priority since a priori it is assumed that all WSN devices must be autonomous. If it is not the case, the key WSN advantages, e.g. autonomous operation, flexibility, are diminished. However, the physical limitations related to the finite capacity of energy storage, e.g. batteries and super capacitors, do not allow the designers to fully realize the concept of ‘perpetual’ operation of sensor nodes. The energy scavenging is considered as a technology which can significantly improve the lifetime of autonomous sensing devices [50,51].

Table 2 shows the power density of some of the ambient power sources. It can be observed from Table 2 that the amount of solar radiation and wind in outdoor conditions is enough to power the sensor nodes. The solar and wind energy sources are not stable though and are highly dependent on the weather conditions. In addition, there is another issue, which is related to the size of the harvesting components which can be relatively big. Small wind turbines which have a blade radius of 6–7 cm can generate around 10 mW. This amount is enough to power the sensor nodes. A solar cell of 100 cm^2 can generate around 1 W. Given the daylight hours

Table 2
Ambient harvesting sources [48–50].

Ambient source	Power density
Solar (Outdoors)	100 mW/cm^2
Solar (Indoors)	100 μW/cm^2
Vibration (1 m/s^2)	100 μW/cm^3
RF (WiFi)	0.001 μW/cm^2
RF (GSM)	0.1 μW/cm^2
Thermal ($\Delta T = 5\,^\circ$C)	60 μW/cm^2
Wind (4 m/s)	5.5 mW

and the average illumination level, the average output is around 200 mW which is enough to supply the sensor nodes.

Since the catalytic and semiconductor sensors are power hungry devices, not all energy scavenging technologies can be efficiently employed to successfully address the lifetime problem. Harvesting of solar radiation and wind are among the key energy harvesting technologies for the hazardous gases detection with the WSNs. For example, in [41] a generic energy scavenging module is designed to supply a gas sensor node for pyrolisis detection. The energy scavenging module can harvest both AC and DC based ambient energy and store it in two energy buffers: super capacitors and Li-ion battery. The module has been tested both in laboratory and real conditions. The goal of experiments conducted in the lab is to ensure that the energy scavenging module can store the solar radiation (DC ambient power supply) and noise (AC ambient power supply) correctly. The entire system has been deployed at a university campus in real conditions.

A CO_2 sensor node powered by the indoor light is proposed in [52]. Although the experimental results demonstrate the sustainable operation of the sensor, the thorough power management is required to effectively supply the wireless transmitter.

In contrast to solar radiation harvesting, RF harvesting can hardly be applied to gas WSN applications. Far-field wireless powering can generate the power density in the range of 20–200 μW/cm^2 with a powering range of ten meters [43]. To get higher values and better efficiency it is highly important to have a powerful transmitter (that is not the case for 2.4 GHz ISM bands) closely located to a sensitive receiver, careful design of power management circuit including receive antenna, impedance matching and rectification [44].

Maximum power point tracking has been also considered as a topic of research and used in the area of energy harvesting [45,46]. In [47], the performances of a 'directly coupled' system and an MPPT one for solar energy harvesting have been compared. In order to evaluate energy harvesting in each system, two outdoor tests were conducted. The first experiment was carried out on cloudy days and the second one was taken place on sunny days. Based on the experiments, the amount of energy achieved by using the MPPT system was not greater than the directly coupled one. According to the authors, this could be associated with the efficiency of the MPPT circuit, which degrades with output voltages lower than 3 V.

A more detailed overview of the energy scavenging technologies for WSNs can be found in [53]. However, only direct solar radiation and wind can provide enough power to support gas sensors. Light, acoustic or electromagnetic waves scavenged in indoor conditions, e.g. industrial premises, can provide current in the μA range only [48], which is not sufficient to ensure proper gas sensor node lifetime.

Due to continuous reduction of the power consumption of sensor nodes on the one hand and increase of the efficiency of the energy harvesters on the other hand the creation of truly 'self-powered' sensing devices is expected in the nearest future.

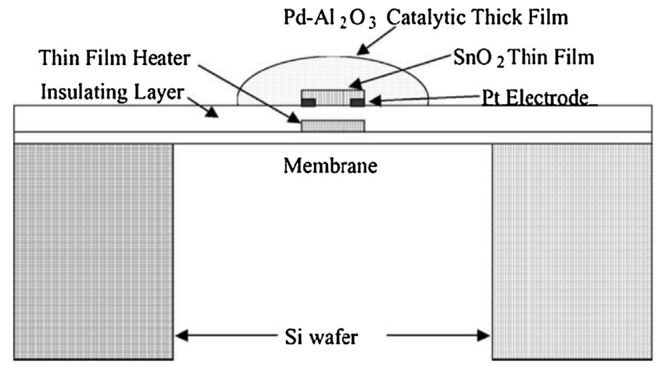

Fig. 2. Sensor cross section (Data from Ref. [33]).

3. Gas sensor technologies for catalytic and semiconductor sensors.

In this section we summarize recent advances in the design of low power catalytic and semiconductor gas sensors.

The typical semiconductor and catalytic sensors produced by world famous companies (Figaro [23], Nemoto [24], Hanwei Electronics [25]) are power hungry devices and, therefore, can hardly be used in WSN application. The lion share of consumed power is spent for catalyst layer heating.

A typical approach to power consumption reduction in semiconductor and catalytic sensors is decreasing the size of a sensitive layer. The aim is to decrease the heating volume consisting of a substrate, a heater on top, and a deposited catalyst. To realize this task, the technology transits from a spiral wired heater (as for the catalytic bead sensor) [23] to a planar sensor [17] where the heater is implemented as a meander on the substrate. In this case the substrate thickness has to be as thin as possible. Generally speaking, the substrate moulds into a membrane. At the same time, this membrane has to be robust enough to sustain the catalyst and high temperature.

The second approach, based on membrane technology [26], provides for the reduction of the heater and catalyst areas. It helps optimizing the power consumption, but results in degraded sensor response. This approach includes two techniques for fabrication of semiconductor and catalytic sensors using membrane technology. The first one is based on thin dielectric membranes, in particular, SiO_2/SiNx [27] (micromachined silicon based technology) and the second one is based on ceramic technology [17]. We discuss these technologies in next sections.

3.1. Micromachined silicon based catalytic and semiconductor sensors.

Micromachined silicon based catalytic and semiconductor gas sensors have been investigated by many research groups due to their low power consumption, excellent reproducibility, possibility of integration, low cost fabrication, small size and portability [28–31]. Micromachined gas sensors are similar in their design (see Fig. 2) [32,33,55]. The main part of the sensor is a membrane made of SiO_2/SiN_x layers with a Pt heater, electrodes, and catalyst on top. Semiconducting layer in semiconductor sensors is typically made of SnO_2, ZnO and other compounds with catalytic impurities on the base of noble metals. The catalyst sensors have a dielectric support impregnated by Pt and Pd metals. The power consumption of these sensors during methane monitoring varies between 30 and 120 mW in continuous measurement mode [32,33]. To the best of our knowledge the most energy efficient catalytic sensor is presented in Fig. 3 [34]. At 450 °C microhotplate consumes about 18 mW. Thermal response time of the heater is around 3 ms. In prin-

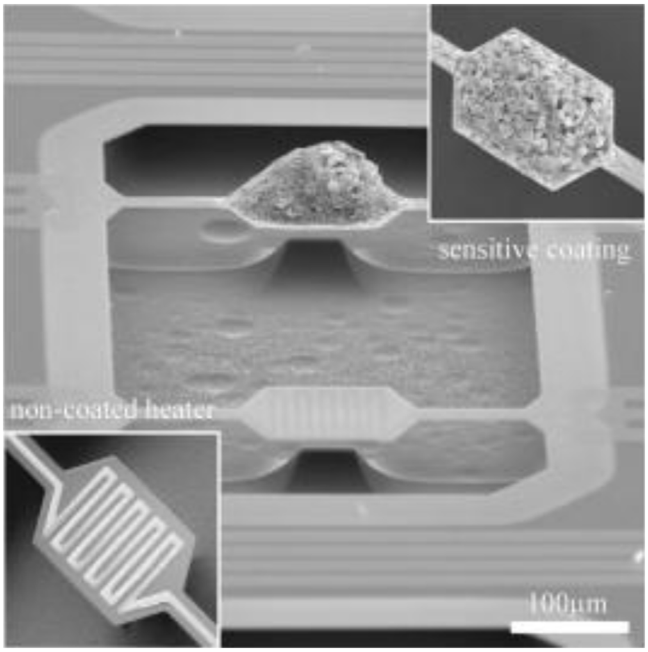

Fig. 3. SEM views of suspended hotplates of a pellistor type gas sensor device. The catalyst containing porous ceramic droplet (top) has a substantial effect on thermal behavior (Data from Ref. [36]).

cipal, MEMS technology has additional capabilities in decreasing power consumption as presented in [35], e.g. the micromachined sensor with optimized microheaters consumes around 2 mW when operated continuously at 300 °C.

In contrast to electronic devices which are typically packed and have the environmentally protected casing, sensors directly contact the environment, which results in deterioration of their parameters. In the case of operation in the harsh environment, the degradation is faster and requires frequent sensor calibration. The best material for fabrication of a sensor's heating element which is not oxidizing at 400–500 °C (for methane) is Pt. At the same time, there are some disadvantages in its application. The main problems associated with the use of traditional silicon based micromachined substrates are the insufficient stability and low fatigue resistance of multilayer silicon oxide/silicon nitride membranes, instability of silicon nitride towards hydrolysis at a high temperature, the poor adhesion of Pt to the membrane, and the poor adhesion of the sensing layers to the membrane material. It is also difficult to expect a good vibration and shock resistance of the substrates.

3.2. Sensors based on ceramic membranes (CeraMEMS).

A number of problems related to the silicon membrane technology could be avoided by using an Al_2O_3 membrane, obtained by anodic oxidation of Al in an electrolyte and subsequent annealing, leading to the formation of an almost homogeneous γ-modification of polycrystalline aluminum oxide [37]. The γ-Al_2O_3 membrane is then stretched on a rigid ceramic substrate with previously drilled holes (3 mm in diameter). This technology could be used for both semiconductor and catalytic sensors. The power consumption of these microhotplates is around 50–70 mW per sensor.

The structure of the CeraMEMS chip is presented in Fig. 4 [37]. It consists of rigid frame made of commercial Rubalit 710TM alumina ceramics (1) with holes; thin alumina film (3) is fixed on this frame with glass binder (2) and covers laser drilled hole (5). On top of this film the sensing layer (4) equipped with meander shaped heater (6) and digit electrode (8), was deposited by screen printing or drop

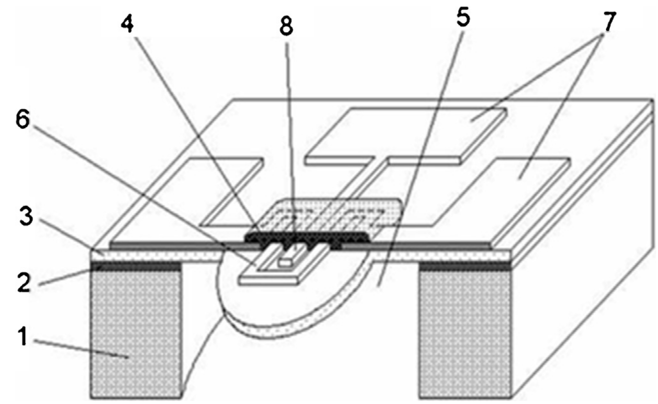

Fig. 4. The scheme of the CeraMEMS chip based on thin alumina film designed for gas sensor application. 1–0.6 mm thick ceramic substrate with holes; 2–glass binder layer; 3–thin alumina film fabricated by electrolyte spark oxidation of aluminum; 4–gas sensing layer; 5–laser drilled hole; 6–meander shaped platinum heater; 7–contact pads to heater and digit electrode; 8–digit electrode to the sensing layer (Data from Ref. [37]).

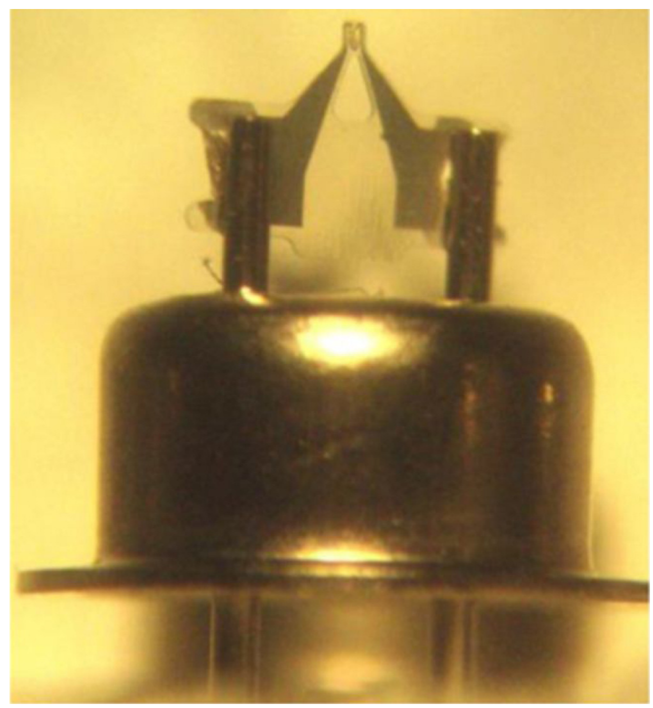

Fig. 5. Optical image of the sensor fixed in the casing TO-8 (Data from Ref. [17]).

deposition techniques. The contact pads to the sensing layer and heater (7) are located in room temperature area.

The technology of microhotplate fabrication does not require complex and expensive equipment, however the value of the required power is still high, because of heat leak along the membrane to the ceramic substrate. Besides, the membrane bends because of thermal expansion during heating, which may lead to its failure.

To address this problem a free wedge-shaped membrane or a membrane only partially linked to a rigid ceramic frame can be used. Sensor supports are 30 μm thick nano-porous gamma alumina membranes fabricated by anodic oxidation of an Al foil [17] (Fig. 5). Micro-heater patterns are formed by lithography on top of the membrane. Micro-heaters are deposited by magnetron sputtering of a platinum target and covered by thin film layer of Al_2O_3 to prevent its degradation. The heated area is about 200 × 200 μm^2.

To avoid bending of the membrane during periodic heating (eventually leading to membrane failure) and to further decrease energy consumption, a free wedge-shaped membrane without linking it to a rigid alumina frame is used [17].

It is necessary to note that the technological obstacles in reducing the size of sensitive elements used in catalytic and semiconductor sensors have currently been reduced. As a matter of fact, there are no technological obstacles for reducing the physical size of the sensitive element. The problem is that the so-called reduction, in particular for the catalytic sensors, leads to a decrease in the volume of the catalyst and, consequently, to decreased catalytically active centers. This reduces the sensor response time and expedites its degradation process.

A promising approach to minimize the sensor power consumption is developed in [38]. The authors propose to save power by decreasing the temperature dissipation via sensor packaging. They explored the possibility by introducing hydrophobic silica aerogel as packaging material owing to its excellent low thermal conductivity and high gas permeability. Experimental results reveal that a significant power decrease of approximately 30% and high sensitivity can be simultaneously achieved for the traditional active pellistor methane sensor with thermal insulation-strengthened packaging with silica aerogel. The power consumption of sensor at 450 °C is 60 mW.

Another way to reduce the power consumption is to reduce the operating temperature (450 °C) of the sensor by the catalyst design [39]. Lowering the operating temperature has a complex effect on the sensor parameters and leads to unpredicted results in terms of sensor operation. At lower operating temperature, the sensor sensitivity, time of reaction, sensor lifetime is a subject to degradation.

More information on the MEMS sensors design can be found in [40].

4. Sensing circuits

The operating principle of catalytic and semiconductor sensors is in changing of their resistance in the presence of gas. There are two sensing circuits typically used for gas sensing: the Wheatstone circuit and a voltage divider. In this section we discuss their pros and cons, as well as their potential from power consumption point of view.

4.1. Wheatstone circuit

The Wheatstone circuit shown in Fig. 6 is the most widely used one for measuring the change in a sensor resistance. It includes two resistors R_1, R_2 and two sensors, active one, R_{act}, and reference one, R_{ref}. R_3 is an optional resistor to measure the heating current. ΔR represents the resistance change of R_{act} during heating, but does not appear in the circuit physically. It is worth noting that R_{act} and R_{ref} sensing elements are physically embedded in one sensor.

The active sensor covered with a catalytic material, is used to conduct the measurement. The reference sensor is identical to the active one but is not covered by the catalyst. This makes it almost insensitive to the gas concentration in the environment and it, therefore, serves as a reference point for detected gas concentration by the active sensor. Also, R_{ref} helps to compensate for environmental factors such as temperature and humidity.

The Wheatstone circuit is a very reliable one since it provides stable response signal that can be used for further analysis directly. However, this circuit has two major disadvantages:

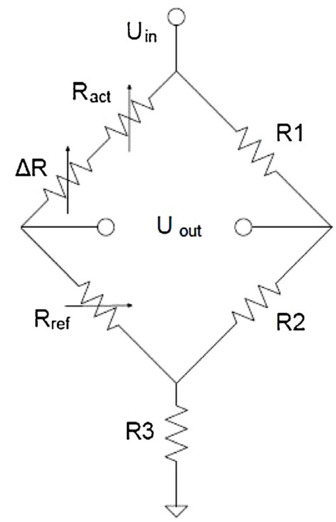

Fig. 6. Wheatstone gas sensing circuit.

1) High power consumption: Since the circuit inherently employs two sensors its power consumption is doubled w.r.t. the voltage divider circuit.
2) Frequent calibration: Since the parameters of the two sensors vary due to the composition of sensing layer (presence and absence of catalyst), frequent 'zero calibration' is required.

Next we discuss the point which has not been discussed in the literature so far. The active and reference sensors have the same initial values of resistance, but their masses are not the same. The Pt-Pd catalyst of the active sensor has a relatively bigger mass as compared to the reference sensor. When a heating voltage is applied to the sensing circuit, the sensors are heated up with different speed due to the difference in their masses. As a result, the values of R_{act} and R_{ref} change differently. Due to this fact, when the sensors are heated up the voltage response (U_{out}) reaches the maximum value. Then this value starts to decrease. The peak value which appears on the response curve, however, does not mean the "real" response of the sensing circuit. The real response resulting from the detection of hazardous gases can be received after the U_{out} is stabilized (both of the sensors have the same temperature). This oscillatory mechanism increases the sensors heating time, as well as the power consumption of the Wheatstone circuit [19].

4.2. Voltage divider

The voltage divider circuit shown in Fig. 7 employs one active sensor R_{act} which forms one arm of the circuit. R_m is a known precise resistor serving for calculation of divider parameters. This circuit does not require the calibration of 'zero offset' due to the application of one sensor and, obviously, requires less power than the Wheatstone circuit with two sensors. The voltage divider circuit has two major disadvantages:

1. It generates a weak response signal that requires additional conditioning using extra hardware components [22].
2. It is not possible to use the traditional measurement procedure since the voltage divider does not compensate the temperature and humidity variation. To compensate for the environmental parameters, e.g. ambient temperature, a measurement procedure based on the four stage heating profile described in Section 5 and a thermo compensation algorithm [56] are applied.

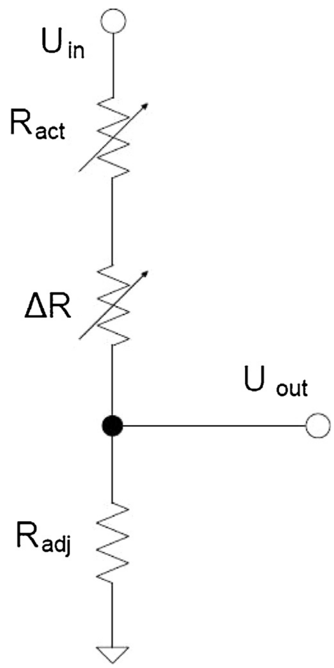

Fig. 7. Voltage divider gas sensing circuit.

In terms of power consumption this circuit is 65% more efficient w.r.t. the Wheatstone one [18].

5. Measurement procedure

The process of measuring the gas concentration with the use of a semiconductor or catalytic gas sensor is implemented at the sensitive layer which changes its conductivity when heated up to 400–500 °C temperature in the presence of a gas, e.g. methane. In catalytic sensors the resistivity of heater is changed due to the gas oxidation reaction on the catalyst layer.

The sensitive layer of semiconductor sensors is implemented as a semiconductor layer which changes its conductivity due to gas absorption. The heating of the sensitive layer activates physical and chemical processes on its surface, thereby increasing sensitivity to gases.

The measurement procedure of combustible gases using these types of sensors consists of a heating process during which the sensitive layer is heated up to 400–500 °C and this temperature is kept for a period of time to receive a response in the case of gas presence in the environment.

Continuous heating results in significant power consumption which contradicts with the WSN paradigm where the sensor nodes are characterized by limited energy resources. To adapt catalytic and semiconductor sensors to WSN nodes and meet the power consumption requirements, a number of measurement procedures based on pulse heating profile have been proposed recently. In this section, we summarize and overview these procedures from the power consumption perspective. Fig. 8 summarizes the measurement procedures for the hazardous gases detection proposed in the literature recently.

5.1. Quasi - Continuous measurement methods

In most gas detection applications there is no need for continuous heating of the sensor. A measurement can be conducted periodically [30]: a sensor node periodically wakes up, conducts a measurement and goes back to sleep mode. In this case the power consumption can be reduced proportionally to the heating duty cycle [41]. This mode of operation results in significant energy savings. At the same time, the sensor design guarantees more than 10 millions of heating cycles [33] that are enough for several years of operation.

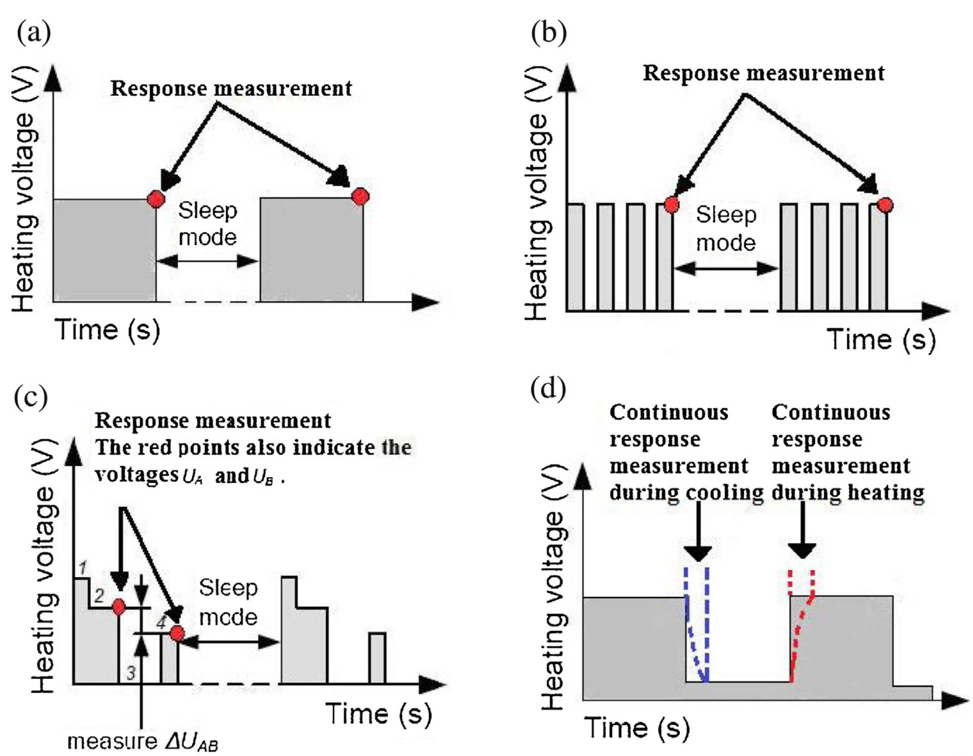

Fig. 8. Heating procedures: (a) Using heating pulse, (b) PWM heating pulses, and (c) Using a four stage pulse (where 1 is a heating pulse, 2 is a temperature support pulse, 3 the sensor is cooled to the second temperature of measurement, 4 is a final heating pulse to guarantee the second measurement temperature.

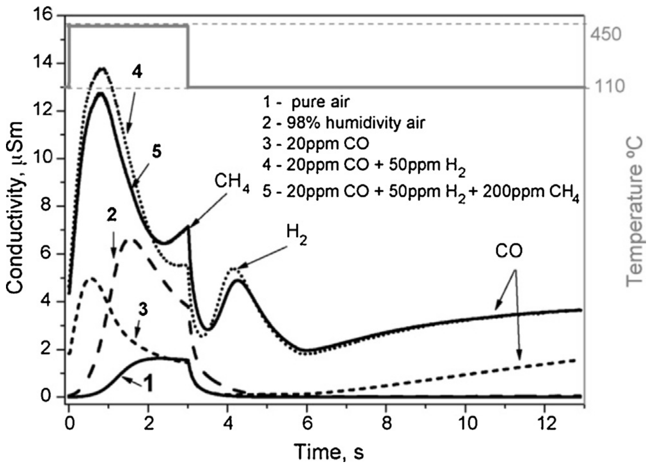

Fig. 9. The response of the sensor operating in cycling pulse heating mode (3 s of heating up to 450 °C followed by 10 s at 110 °C) to methane, carbon monoxide, and hydrogen (Data from Ref. [16]).

As mentioned earlier, the sensing layer could be heated up by a single pulse or PWM pulses (see Fig. 8(a). For example, in [41] and [8] PWM based heating profile is applied to the sensing circuit. It is obvious that the less the heating duty cycle is the less heating energy is spent. However, between the PWM heating pulses the sensor cools down and instead of paying less the system pays more in terms of energy. This problem is carefully investigated in [41] where the authors conclude that 70–80% duty cycle is the best trade-off between performance end energy efficiency.

In [54] the authors propose a Temperature-Programmed Sensing (TPS) technique that applies PWM-like heating pulses to a gas sensor and records the sensor response during heating. Depending on application and environmental conditions PWM pulses can be adjusted in terms of width and duty cycle. The feature of this approach is that the response patterns are specific to a particular gas.

5.2. Dynamic mode of operation

5.2.1. Temperature scanning

Periodic heating of the sensor for the measurement can not only directly reduce its energy consumption, but also indirectly.

As the temperature of the sensor increases and decreases periodically (i.e. temperature scanning), this temperature variation can be used to gather additional information on the gas composition and to find ways of improving sensitivity and selectivity of the measurement [42].

In particular, during the transient response of a semiconductor sensor, various gases in a gas mixture can be separated (Fig. 9) and their concentration can be calculated (for example, H_2, CO, CH_4, humidity) [16].

First, the sensor is heated up to 450 °C. Then, the sensor is cooled down to 110 °C (at this temperature moisture does not adsorb to the sensor surface). However, instead of a single measurement of conductivity the system performs a series of conductivity measurements while the sensor cools down. Analysis of the local maximums on the response curve helps to infer dangerous gas presence and its concentration in the environment [16]. This measurement procedure takes 10–12 s. It is worth noting that in contrast to [41] and [8] this approach requires updated calculation procedure for calculation of gas concentration based on sensor response. In fact, the response signal is analyzed from the sensor dynamics point of view, e.g. how the sensor cools down and what happens during this process. In general, this approach ensures low power sensing (up to several mW) with high selectivity and quick detection of H_2, CO, CH_4. A sensor lifetime is estimated as 7 millions on-off cycles at 450 °C. This example demonstrates that the periodic measurement mode is useful for both the power consumption reduction and selectivity improvement.

5.2.2. Specific profile heating

To achieve further reduction of the sensing circuit power consumption, the ‘differential’ measurement procedure has been proposed in [17] and [18]. Instead of widely used Wheatstone circuit the authors propose to employ a single active gas sensor embedded in the voltage divider circuit (see Fig. 8c). The idea is to have this single sensor operating as both an active and reference sensor. In order to compensate for the environmental parameters, i.e. temperature and relative humidity, it was proposed to conduct the measurement at different temperatures – above and below a gas oxidation temperature on the catalyst as it is shown in Fig. 8(c). As the influence of environmental parameters on the sensor is the same at different temperatures, this is a way to compensate for the humidity, ambient temperature and other uncontrolled factors on the sensor response.

For example, the heating temperatures used in the measurement of methane are defined with respect to physical process during methane burning. Pulse 1 is the main heating pulse ensuring the quick sensor heating to moisture evaporation. The objective of pulse 2 is to provide the sensor with the temperature stabilization at 450 °C and let the system to conduct the first measurement at the end of this pulse. The first two pulses are followed by pulse 3 at 200 °C. Final pulse 4 ensures the sensor temperature stabilization at 200 °C and the second measurement is conducted at the end of this stage.

For the output voltage it is taken the voltage difference between U_A and U_B. (Fig. 8 c). The first value, U_A, is the voltage at the end of the second stage of pulse heating (heats the sensor up to 450 °C). The value of U_B is the voltage at the end of the fourth stage of pulse heating (200 °C). It was demonstrated that the measurements are not influenced by moisture. The heating pulse duration and applied heating voltage were optimized in terms of the minimal energy consumption and independency from moisture and environmental temperature. This approach allows the reduction of power consumption up to 1.2 mW [17].

However, the response voltage of this circuit is lower w.r.t. the Wheatstone circuit. This disadvantage can be addressed by response signal conditioning and filtering [22].

In fact, there are a number of options in terms of the heating pulse voltage and duration. The bottom line is that only one sensor is used in the sensing circuit and acts as the reference and active one interchangeably. It is realized by heating it up to two different temperatures and conducting the measurements after these heating procedures.

6. Future outlook

The average power consumption of wireless gas sensor nodes has significantly dropped recently as it is shown in Table 3. However, in the nearest future the power consumption of catalytic and semiconductor gas sensors will not achieve the level of typical temperature and humidity sensors as presented in Section 2. It will not happen due to the technological barriers associated with the catalytic and semiconductor sensors working principle based on heating. At the same time, the application of these sensors in WSN ensures a trade-off among the power consumption, performance and safety requirements.

Further progress in making the gas sensor nodes autonomous can be achieved by (i) reducing the power consumption of the electronic components (gas sensor, MCU, transceiver), since the power

Table 3
The advancements achieved in decreasing power consumption of gas sensor nodes.

	Ho [5]	Wobscholl [20]	FlyPort [21]	Somov 2011 [8]	Yokosawa [7]	Somov 2012 [18]	Somov 2014 [22]
Application	Hazardous gases detection	Toxic gases monitoring	LPG, natural/town gas	Combustible gases monitoring	Hydrogen monitoring	Hazardous gases monitoring	Hazardous gases monitoring
Sensing power consumption	1550 mW	1000 mW	800 mW	264 mW	200 mW	124.30 mW	85.68 mW
Response time	N/A	up to 110 s	up to 10 s	1.50 s	up to 1.20 s	0.70 s (2 sensors) 0.56 s (1 sensor)	0.65 s (2 sensors) 0.50 s (1 sensor)
Sensor	Laser spectroscopic	Catalytic/semiconductor	Semiconductor	Semiconductor	FET	Catalytic	Catalytic
Features	Detects any gases, accurate measurements, high power consumption	Automatic calibration	Inaccurate measurements, frequent calibration required	Wheatstone circ., accurate measurements	Long sensor response	Differential circuit, accurate measurements, no calibration required	Differential circuit, accurate measurements, no calibration required

consumption of digital systems reduces by half every two years, and application of the state-of-the-art power management solutions and energy scavenging technology, (ii) increasing the capacity of the energy storage (battery capacity doubles every ten years), (iii) performing the careful analysis of the sensor node power consumption, its operation and design using WSN simulators [58], (iv) introducing intelligent and cognitive algorithms during sensing.

In this section we discuss two promising approaches (hybrid power sources and intelligent sensing) in the context of 'future work'.

Hybrid energy harvesting is a technology capable of harvesting the ambient energy from various ambient sources. Since ambient energy sources have an intermittent nature, it is expected that hybrid harvesting will secure 'continuous' ambient energy scavenging even though one of the sources is unavailable. In fact, hybrid energy scavenging has been already used in some WSN monitoring applications [59,60]. The prototypes have evolved from lab ones [61] to real deployments [50], e.g., for structural health monitoring. However, more research efforts are still required in this field to study hybrid energy scavenging in more detail, analyze its pros and cons, potential applications and real world deployments in the scope of hazardous gases detection.

Alternative approaches for energy aware gas sensing with WSNs are grounded on intelligent techniques. For example, the bottom line of context-adaptive approache is to embed a Pyroelectric Infrared (PIR) sensor in a gas sensor node. The PIR sensor collects the information on presence of people to adapt sensing duty cycle [57].

A similar context aware approach based on the Internet of Things paradigm and cognitive technologies is presented in [62] to address the problem of fire detection. The approach is grounded on the interchangeable exploitation of two heterogeneous WSNs (in terms of employed sensors and their power consumptions) depending on context. Key contribution of this work is a cognitive framework where virtual objects of real sensor nodes are created and enriched with context data to facilitate the inference procedures. Depending on the context and utility cost of the nodes, one of the WSNs switches to active mode to enable reliable fire detection while ensuring safe monitoring.

However, while demonstrating good performance, the intelligent approaches applied for the gas sensing are carried out with no reference to any standards making them practically useless for real deployments.

7. Conclusion

In this work, we have performed a survey of power consumption optimization approaches for wireless gas sensor nodes. In the beginning we have identified that semiconductor and catalytic sensors are the most suitable gas sensing technologies for their application in WSN: they ensure good performance and reasonable power consumption while meeting the requirements of safety standards.

The focus of this survey is on the optimization approaches for power management, gas sensor technologies, sensing circuits, and measurement procedures – the aspects which significantly contribute to the power consumption of the gas sensor nodes. Since the gases detection is considered to be one of the emergency applications, we discuss the power consumption optimization approaches with respect to the safety standards where applicable.

We believe that this work helps both developers and researchers to identify and overcome challenges associated with the powering of gas sensor nodes and open up wide vista for autonomous gas detection applications.

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