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Design of Smart Dust Sensor Node for Combustible Gas Leakage Monitoring.

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Abstract—**In this work we present the results of design of smart dust sensor platform for combustible gas leakage monitoring. During the design process we took into account a lot of combustible gas sensor specific problems such as their huge power consumption, the necessity to work in explosive environment and sensor parameters degradation. To decrease power consumption we designed specific energy efficient algorithms for measurements. The resulting average power consumption of the node is low enough for one year autonomous lifetime. The methods and algorithms which was designed are very promising for catalytic combustible gas sensors.**

I. Introduction

SMART dust is a term which was introduced in 2001 by Kristopher Pister and it is related to tiny devices for environmental monitoring with self-organization feature. Such devices should be able to measure different physical parameters, to process data and to send it to the end user through wireless data transmission channel. The main functional block of the "smart dust" is a sensor node which consists of microcontroller, memory, wireless transceiver, power source and one or several sensors (Fig. 1).

The power source of the sensor node is typically batteries. However, in the last time several platforms were designed which use supercapacitors, alternative power sources or their combination. Sensor node generally use microcontrollers which combine enough computational capability and performance and low power consumption. All these functions are very important for autonomous "smart dust". Wireless transceivers very often comply IEEE 802.15.4 standard and ZigBee specification. Such devices are low power and are able to transmit data for the distances up to 30-50 meters. The most popular sensors are temperature and humidity sensors and accelerometers. They are widely used for "smart dust" because of their low power consumption.

During design process of wireless sensor network for gas monitoring it is necessary to take into account that combustible gas sensors consume power up to several hundreds milliwatt. At the same time it is necessary for "smart dust" sensor nodes to have as long autonomous lifetime as it is possible. To increase sensor node autonomous lifetime, developers strive to select electronic components with low power consumption, to use energy harvesting technologies [1], [2], to equip sensor nodes with power sources with huge capacity [1], [3] or to use "smart" algorithms and methods [4], [3], [13] to decrease power consumption.

In this work we present the results of design of "smart dust" sensor node for combustible gas leakage monitoring as well as the results of design of energy efficient measurement algorithms for power consumption decrease.

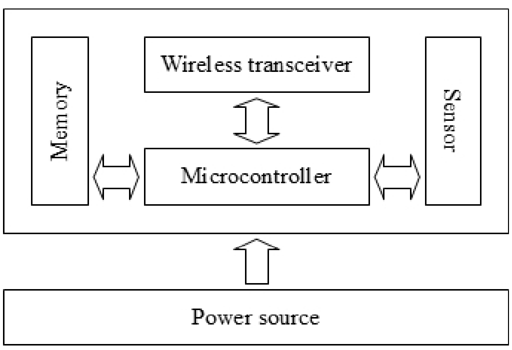

Fig 1. Typical structure of the "smart dust" sensor node.

Fig 2. The smart dust gas sensor node prototype.

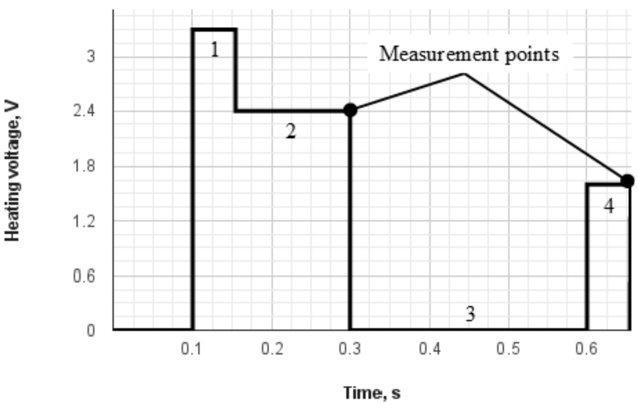

Fig 3. Multistage pulse heating profile.

At present time there are a lot of "smart dust" platforms. Ones of the firsts platforms are TelosB [5] and the family of modules MICA (MICA/MICA2/MICAz) [6], [7]. These platforms used light, temperature and humidity sensors, but end user was be able to add almost every kind of sensors through available connectors and interfaces.

After that commercial modules took their place [8], [9]. With that, typical sensor node became modular. The platform now is a motherboard and it is possible to connect other boards to it (with sensors, wireless transceivers and data processing modules). The main philosophy of these platforms is to provide every possible configuration of the sensor node to the end user, both from software and hardware points of view, using all platform possibilities.

However, all available sensor nodes do not take into account all problems which are related with using wireless sensor networks for combustible gas leakage monitoring. Particularly, such problems as huge power consumption of catalytic, semiconductor and optical sensors, the necessity to work in explosive environment and sensor parameters degradation.

The smart dust sensor node (Fig. 2) which we present in this work is able to work with catalytic combistible gas sensors.

Heating-up of the sensor to working temperature is performed using PWM-controlled voltage. With that, sensor temperature is controlled using complex algorithm. Sensor response measurements are performed in different temperature points. And these sensor response measurements are used to calculate combustible gas concentration.

II. Experimental Details

In this paper we used the commercial catalytic sensors manufactured by NTC IGD, Russia. The sensor box height is 9.5 mm and diameter 9 mm, power consumption is 200 mW in the continuous measurement mode. Its relatively low power consumption (compare to Figaro, Nemoto and Hanwei) is achieved by applying a heater implemented as 10 µm platinum micro wire in glass insulation (2 µm). The active sensor has a platinum micro wire covered by porous gamma alumina oxide material that is used as catalyst support for catalytically active metals (mixture of Pd and Pt). In order to impregnate the catalyst support by the catalytic metal, salts of palladium chloride ($PdCl_2$) and platinum acid (H_2PtCl_6) are used. After annealing at 500 C, noble metal clusters are formed in the catalyst support.

Circuits for gases detection with catalytic sensors are commonly based on the Wheatstone bridge, which includes two resistors and two sensors, one active and one for reference. Most of the power goes into the sensor heating process (about 450 C for methane detection), required to perform the measurement. The power consumption is about 200 mW for Wheatstone bridge and that's much higher than suitable for wireless application.

Excluding the reference sensor decreases power consumption. But at the same time it's necessary to compensate atmosphere humidity and temperature which usually performed by reference sensor. This compensation was made by applying the specific multistage heating pulse. This method was offered and discussed in works [4], [3], [14].

Here we use four stages for every multistage pulse (1-4 regions in the diagram, Fig. 3).

The first and second stages provide the sensor heating to the external diffusion region of catalysis and the partial evaporation of surface water (~450 C). These stages are followed by a pause (third stage) during which the surface is

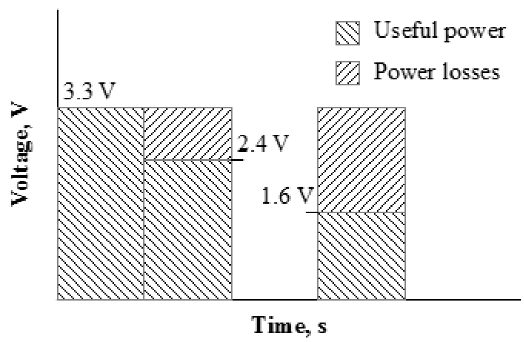

Fig 4. Useful and wasted power during multistage heating pulse in DAC circuit design.

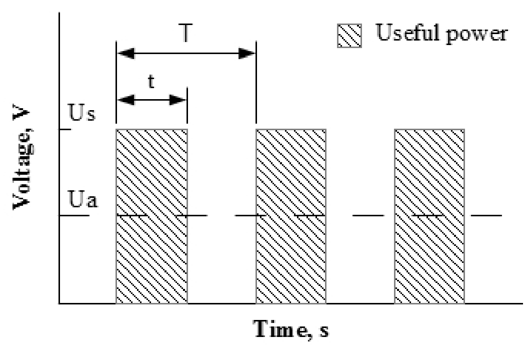

Fig 5. Pulse-width modulation parameters.

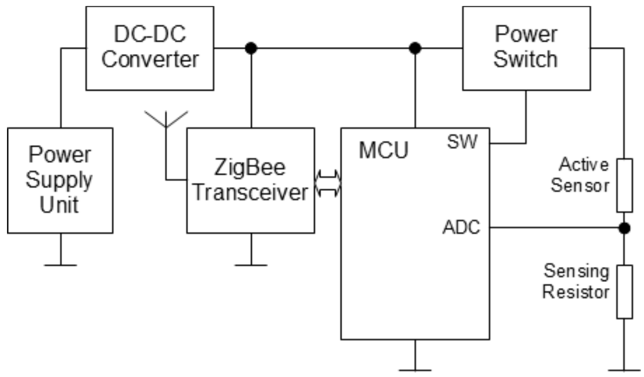

Fig 6. Block diagram of the wireless gas sensor node.

not heated. The final fourth stage heats the sensor to the beginning of the kinetic region of catalysis (~200 C). After this pulse, the element cools down to ambient temperature. Heating voltages for the stages are 3.3 V, 2.4 V, 0 V and 1.6 V respectively.

The measurement result is the difference between sensor voltages at two different temperatures (measurement points in the diagram).

Multistage heating pulse is formed by applying different levels of voltage to sensing circuit. Traditionally it can be done using DAC with buffer amplifier. But in this case relatively huge amount of power is wasted by means of power dissipation on buffer amplifier (Fig. 4). Another way is to generate these levels using pulse-width modulation.

Pulse-width modulation (PWM) is frequently used to heat the sensors for working temperature [10] because it allows one to change the average voltage with fixed voltage from power supply.

Pulse-width modulation is the method of regulation of average voltage value on the load by controlling pulse duty ratio.

The main parameters of PWM are its period (T) or frequency, pulse width (t), supply voltage (U_S) and average voltage (U_A) on the load. These parameters are illustrated in Fig. 5.

The average voltage of PWM can be solved using following equation

$$U_A = \frac{t}{T} U_S \tag{1}$$

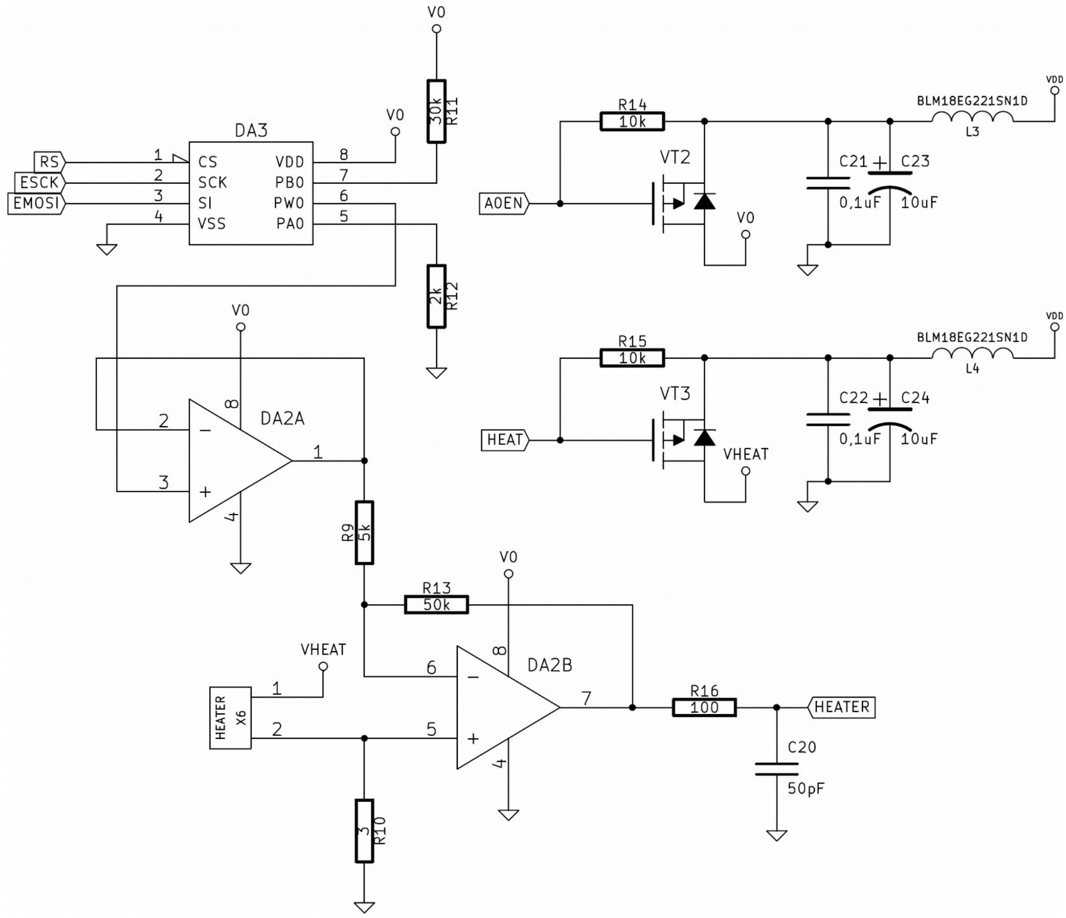

Fig 7. Sensing circuit for multistage pulse with PWM heating.

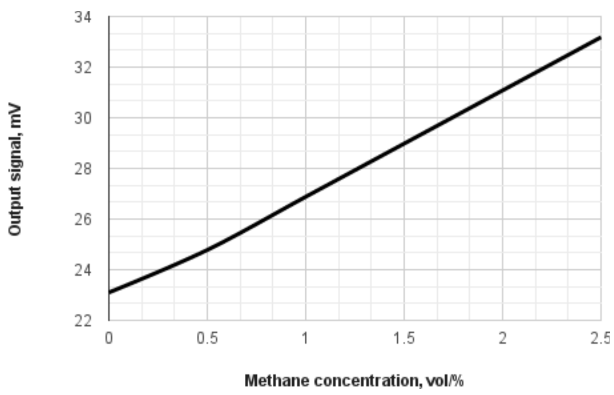

Fig 8. The dependence of the output signal of the sensor on the methane concentration.

As it follows from this equation, for the same PWM frequency and supply voltage changing pulse width it's possible to regulate average voltage on the load.

III. Sensor Node Design

The full block diagram of the wireless gas sensor node is presented in Fig. 6. The sensor node is based on an AtXmega32A4 microcontroller and use an ETRX3 communication module. The selection of the MCU was mainly driven by the following requirements: low power consumption, on-chip temperature sensor, and good ADC integrated in MCU.

The wireless communication unit employs the low power ETRX3 wireless modem supporting IEEE 802.15.4 standard (ZigBee specification) and transmitting in unlicensed 2.4 GHz ISM band. The modem has an integrated chip antenna used in this design (up to 25 m) and a connector for an external antenna to enable a boost mode allowing data transmission for up to 350 m. Besides that, the modem has a number of self-x features enabling, for instance, WSN self-configuration and self-diagnostics which significantly reduce WSN debugging and deployment time.

Voltage conversion is performed by a DC-DC converter TPS63060 to provide maximum efficiency. The device generates stable output voltage of 3.3 V from 2.5 V to 12 V on its input.

Sensing circuit is presented in Fig. 7.

Since it is necessary to have long autonomous lifetime for wireless sensor node, all measurements are performed periodically. But at the same time, according to safety standards [11], [12], sensor node response time should be less than 20 seconds. Therefore, it is reasonable to perform two measurements every 20 seconds to assure this claim. To maintain low power consumption between measurements, the measurements circuit is turned off using power switch based on VT2 transistor.

As it was said before, sensor heating is performed using signal with pulse-width modulation. Here we use PWM frequency of 10 kHz. The average heating voltage is regulated by changing pulse duty rate with fixed power supply voltage. Therefore, with power supply voltage value of 3.3 V and voltage values for pulse stages of 3.3, 2.4, 0 and 1.6 V, duty rate values are 100, 73, 0 and 48 percent respectively. Voltage switching is performed using VT3 transistor. Since this switch also provides power supply for sensor itself, all measurements are performed with activated heating.

The sensor signal is the voltage from resistive divider which consists of sensor itself and reference resistor. The signal goes to the amplifier with gain value of 10.

Another input of the amplifier is connected to the output of voltage reference circuit. This circuit provides reference voltage for different stages of multistage pulse to exclude constant part of the signal from the output.

The circuit consists of resistive divider which is based on digital potentiometer. This potentiometer controls the reference voltage value. This voltage goes to the buffer amplifier. The output of this amplifier is the output of the circuit.

For all measurements built-in ADC of MCU with internal 1 V reference voltage source is used.

IV. Sensor Response

As it was said before, the measurement result is the difference between sensor voltages at two different temperatures. The first value is the voltage at the end of the second stage of pulse heating (which heats the sensor up to 450 C and lasts for 190 ms). The second value is the voltage at the end of the fourth stage of pulse heating (which heats the sen-sor up to 200 C and lasts for 550 ms). This is done to compensate the absorption of moisture on the sensor surface that occurs between two cycles, and influences the quality of the measurement.

The dependence of the output signal of the sensor on the methane concentration is shown in Fig. 8. The value of the signal is changed from 23 mV for 0% of CH_4 to 33 mV for 2.5% of CH_4. Therefore, sensor sensitivity for this method is about 4 mV / %CH_4.

The sensor node operates as a two-threshold device. Threshold values are 0.5 and 1 % vol. If the methane concentration is less than 0.5 % vol., there is no reaction from the sensor node. If the concentration is more than 0.5 % vol. methane, sensor node provides the light and sound alarm. This alarm is different for every threshold. At the same time, after every threshold is exceeds, node sends specific information to the data sink node.

V. Power Consumption

The power consumption of the wireless sensor node is presented in Fig. 9.

As it was shown before, the advantages from PWM heating are in second and fourth stages of multistage pulse. For second stage the resulting power consumption is 150-160 mW. For fourth stage it is less than 80 mW. The average power consumption for overall multistage pulse is 81 mW. This value includes data transmission.

Measurements are performed periodically with period length of 10 seconds. The length of multistage pulse is about 0.6 seconds. The average power consumption, including data transmission, for overall period is about 4.9 mW.

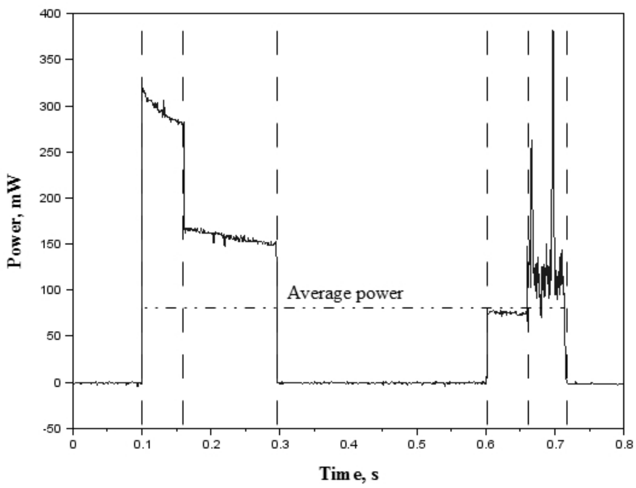

Fig 9. The power consumption of the wireless sensor node.

Since node power consumption is relatively low, the power consumption of data transmission is large enough part in overall power consumption.

The average power consumption of that data transmission cycle is about 125 mW. And its length is about 0.06 seconds. The average power consumption of multistage pulse including data transmission is about 81 mW. And its length is 0.6 seconds.

So the length of data transmission is about 10% of the pulse length. And during this time the power consumption is much higher than average values.

At the same time, usually it doesn't necessary to send data every time than measurements were made. It's much reasonable to transmit it only when gas concentration was changed or in other emergency situations.

The average power consumption excluding data transmission cycle is about 77 mW. The average power consumption for overall period in this case is 4.6 mW. These values are about 5% lower.

These power consumption values are relatively low. Since capacity of a single cell lithium battery of D type is typically 15000 mAh, its voltage is 3.6 V and there are 8760 hours a year, the average power consumption for one year sensor node lifetime is no more than 6 mW. Therefore, the average power consumption of the node is low enough for one year autonomous lifetime. This duration also complies with safety standards which claim to perform gas sensors calibration every year.

VI. Conclusion

In this work the design of the "smart dust" sensor node for wireless sensor network for combustible gas concentration monitoring was presented.

The analog and digital circuits and energy efficient algorithms for sensor response measurements were designed. The parameters of designed sensor node was investigated.

The calculations of methane concentration were made using analysis of commercial catalytic methane sensor response in multistage pulse heating mode of operation which includes four heating stages. With that, sensor heating in every stage was performed using PWM voltage regulation unlike traditional heating with constant voltage.

It was shown that PWM regulation allows to save about 20% of power which sensor consume. Particularly the average power consumption for multistage pulse is 81 mW. And for 10 seconds measurement period the average power consumption value is about 4.9 mW.

The power consumption values provides the autonomous lifetime of the node more than one year. Therefore, the methods and algorithms which was designed are very promising for catalytic combustible gas sensors.

Acknowledgment

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