Microcontroller based Power Efficient Signal Conditioning Unit for Detection of a Single Gas using MEMS based Sensor

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Abstract-A low power MEMS based sensor along with the embedded power efficient signal conditioning unit (Microcontroller based), which can be used with any suitable sensor-network to detect and quantify variations in a particular gas concentration, has been reported in this paper. The power consumption of the MEMS gas sensor is ~ 70mW to 100mW depending upon its operating temperature (150-250°C) and that of entire signal conditioning unit (consisting of low noise amplifier, switch, microcontroller and power management chip) is ~ 36mW in the ON state and only ~7.2µW in OFF state (sleep mode). The test gas in this particular case was methane for which sensor resistance varied from 100KΩ to 10KΩ. This hybrid sensor system is very much suitable for detecting a single gas with display of corresponding gas concentrations and subsequent alarming if the threshold limit is crossed.

Index terms: MEMS, Gas sensor, Low power, Microcontroller, Signal Conditioning

I. INTRODUCTION

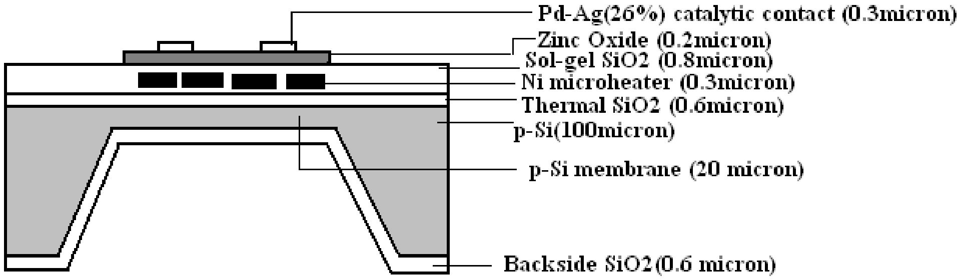
A Signal-conditioning unit for gas Detection has in the recent years been a very useful product for the field engineers especially in hazardous environments and industries to monitor production. Engineers can determine at any point of time as to what is the concentration level of a particular gas. In application field like mines, it can add as an extra measure of safety and bring in reliability. In large industries where automation needs to be brought in, this can serve as a monitoring device and provide feedback [1-10]. The modern sensor technology demands the signal conditioning unit to be preferably present on the same chip as that of the sensor so that the different non-idealities can be taken care of [1]. MEMS (Micro Electro Mechanical Systems) technology has recently been employed in sensor technology in miniaturization of the devices, low power consumption, faster response and greater sensitivity [2]. In case of gas sensor particularly, sensor platform was miniaturized using either bulk of surface micromachining of silicon platform and thereby leading to lower power consumption owing to lower thermal mass of substrate [3-9]. To achieve the lower operating temperature at a relatively low cost, a modified structure of sensor has been proposed employing nanocrystalline ZnO as the sensing material and nickel as microheater element instead of commonly used platinum or polysilicon [10].

Electronic processing techniques may be used to combine the responses of the different gas sensors to the causative stimulus, and also their responses to the target gas if both are responsive thereto, so as to provide a sensor output that is related to the concentration of the target gas, by reducing or canceling out the effect of the other interfering stimuli. Conventional signal processing techniques can be used for this purpose, for instance the various responses of the sensing electrodes may be digitized and subsequently processed, or combined in analogue form. For integrated sensor application, for hazardous environments like underground coalmines where continuous monitoring of hazardous gas concentration is required it is extremely desirable that the entire signal-processing unit capable of amplifying low signal level output from the sensor as well as transmitting the modified signal to remote control station, should be integrated along with the sensor platform [11,12].In our earlier work we reported on such integrated MEMS sensor with ASIC design of the signal conditioning unit [13]. There are also some reports on the development of integrated gas sensor systems with log- invertor circuits for linearising the output voltage [14]. Oscillator circuits have also been reported to be integrated with the gas sensor for conversion of voltage to frequency providing improved resolution [15]. However no report has so far been published on microcontroller based discrete signal conditioning of MEMS based gas sensors. For many applications instead of integrated sensor platform such discrete systems using available standard ICs might be useful due to its low cost, ease of availability and ease of changing components and thereby offering some kind of flexibility which was not possible with predetermined ASIC .

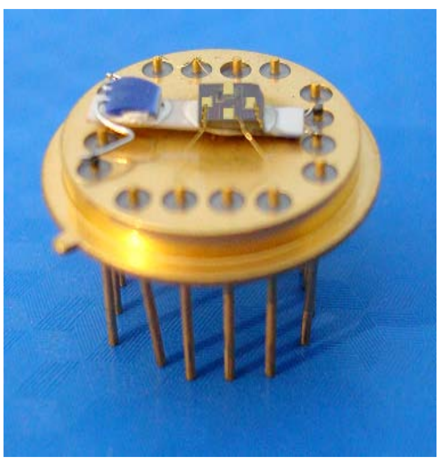
In this paper we also report the integration of the microcontroller based signal conditioning unit with the sensor output for efficient detection and alarming. The power consumption of the MEMS gas sensor is ~ 70mW to 100mW depending upon its operating temperature (150-250°C) and that of entire signal conditioning unit (consisting of low noise amplifier, switch, microcontroller and power management chip) is ~ 36mW in the ON state and only ~7.2µW in OFF state (sleep mode). The test gas in this particular case was methane for which sensor resistance varied from 100KΩ to 10KΩ.

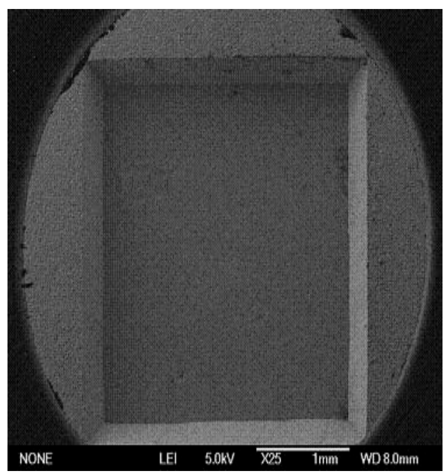
II. ZnO BASED MEMS GAS SENSOR FABRICATION AND CHARACTERZATION

As reported in our earlier publication [10] for fabricating ZnO based MEMS gas sensor, p-Si <100> of resistivity 1Ω-cm (100µm thick) is used as the substrate. On top of that a thermal insulating SiO_2 layer (0.8µm) was grown by thermal oxidation (~1100ºC). After opening window for micromachining by lithographic technique on the backside, bulk micromaching was carried out with EDP (Ehylene Diamine Pyrocatechol) solution at a temperature of 85°C, which results in a silicon membrane of 3mm by 3mm by 20µm dimensions. A backside silicon oxide layer (0.8µm) is grown on the membrane to improve thermal isolation and reduce power dissipation. Nickel is used as a microheater element instead of platinum or polysilicon because of its relatively high resistivity, low cost, ease of fabrication and acceptable durability. Particularly, when the maximum desired temperature is around 100-150^{0}C, nickel film is good enough to act as the heating element. A 0.2 µm nickel layer was deposited on SiO_2 covered front side of the sample by e-beam (10^{-6} mbar) evaporation technique.The microheater was fabricated using conventional lithography followed by nickel etch back technique. A 0.6 µm SiO_2 layer, acting as an electrical isolation between the heater and the active layer, was then deposited on Ni microheater by sol-gel method. The active area was having a dimension of 1.3 mm × 1.3 mm at the center of the membrane. The total sensor area was 4 mm × 4 mm. The lines of meander shaped microheater were 50 µm wide and were separated also by 50 µm. The fabricated heater resistance was about 150 to 170Ω. The active ZnO layer was deposited by solgel method by spin coating technique. Finally the samples were annealed at 350^{o}C for 30 min for producing nanocrystalline ZnO. The entire process was repeated for three times and a ZnO film of ~900 nm thickness with the particle size ranging from 45 nm to 75 nm and average pore diameter of ~56 nm was produced (Fig. 1(c)). Pd-Ag (26%) catalytic contact was deposited on ZnO by an e-beam deposition method (10^{-6} mbar) using Al metal masks. A two dimensional schematic drawing of sensor structure fabricated is shown in Fig. 1(a) and the photograph of the mounted sensor is shown in Fig. 1 (b).



(a)

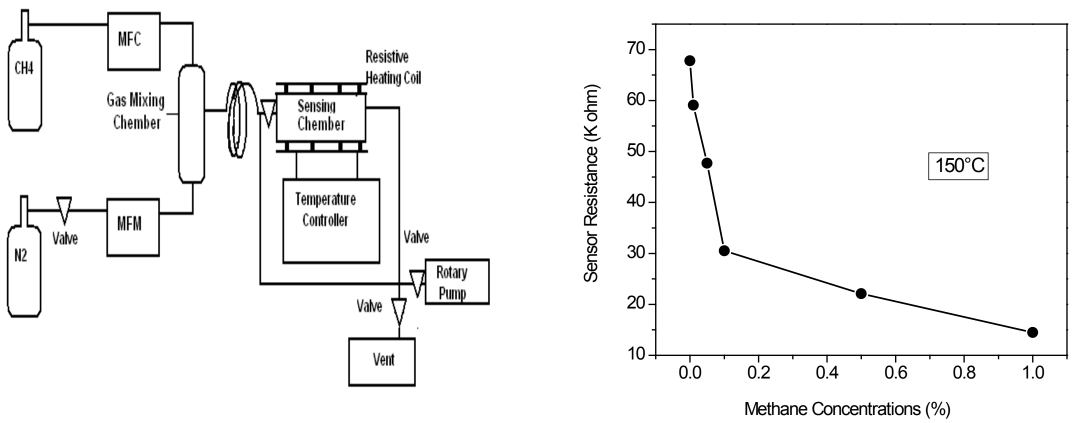




(b) (c)

Figure 1.(a) Two-dimensional schematic view of nanocrystalline ZnO based MEMS methane sensor (not to scale) [13] (b) photograph of the mounted sensor [10] (c) SEM image of the backside micromachined Si substrate [10]

For sensor study high purity (100%) methane gas and high purity (99.99%) N_2 in desired proportions were allowed to flow to the gas-sensing chamber through a mixing path via an Alicat Scientific mass flow controller and a mass flow meter for keeping the mass flow rate and thus the concentration of the methane gas constant throughout the experiments. The gas pressure over the sensor device was 1 atm during the experiments. The resistance of the sensors in the presence and absence of CH_4 was measured by a Keithley 6487 picoammeter/voltage source. The schematic of the gas sensor characterization setup is shown in Fig 2 (a).



(a) (b)

Figure 2: (a) Schematic of the gas sensor characterization setup (b) Sensor resistance as a function of methane concentrations at 150°C [13]

The optimum operating temperature was found to be 150ºC. The variation of sensor resistance at an operating temperature of 150 ºC with different concentration of methane in the N_2 is shown in Fig.2. The response magnitude S, is expressed in terms of sensor resistance in air (R_a) and in test gas (R_g) as follows:

$S=(R_a -R_g) /R_a$

The sensor resistance varied from ~70KΩ to 15 KΩ corresponding to 0.01% to 1.0% methane in N_2.

III. DEVELOPMENT OF MICROCONTROLLER BASED LOW POWER SIGNAL PROCESSING UNIT AND TEST RESULTS

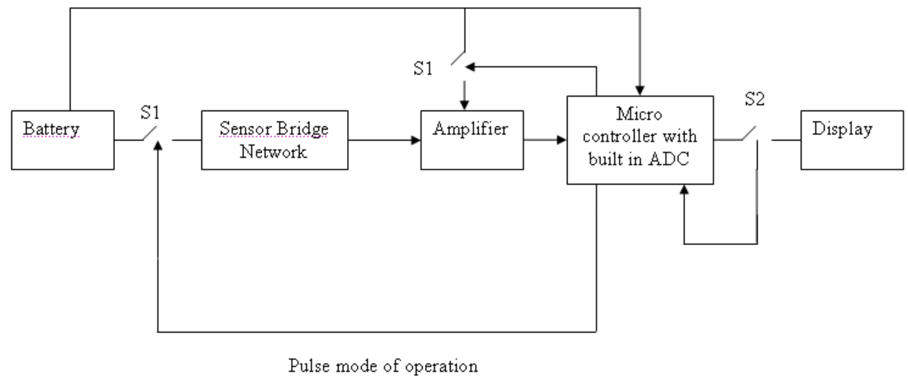


Figure 3. Schematic Diagram of the microcontroller based signal conditioning unit for detection of a single gas

Fig 3 represents the basic scheme for implementing microcontroller based signal conditioning unit. Here same type (low voltage, high bandwidth bus switch) of two switches (CBQ3306A, Texas instruments) S1 and S2 has been used for efficient power management purpose. Its main advantage of this kind of switch is, it has very low and flat ON-resistance (R_{ON}) value over entire operating voltage (2..3-3.6V) range with a very low power consumption. When switch S2 is not pressed , meaning thereby, the user is not interested in measuring and displaying the gas concentration at that time, the microcontroller is in the LMP1 state which is the lower power consumption state (drawing a current of around 2uA only from battery) and switches (S1) remained turned off which implies the amplifier is not powered up by the battery source and there will be no display ,as a result this mode as can be said as "Sleep Mode " because during this interval power drawn from source is minimum as all the main power consuming blocks like amplifier-chip, display and the sensor bridge-network are in off state. Switches (S1) are controlled by the microcontroller. The total power consumption in the sleep mode is only 7.2µW. Whenever the user wants to measure the gas concentration the switch (S2) has to be pressed which brings out microcontroller from Low POWER MODE1 (LMP1) (in low power mode CPU is disabled but the clock remains active) state into normal active state and then microcontroller turns on switch S1 to activate the amplifier and also the sensor bridge-network with a constant voltage source (circuit draws a current of around 10mA in this mode). Bridge network is driven by a constant voltage source implemented by TPS63002 (provides 3.6V voltage).Whenever any interrupt occurs, microcontroller comes out of this state to active mode, performs the function and again returns to LMP1 waiting for another interrupt. Thus the overall power handling is performed in an efficient manner. The microcontroller then turns on switch S1 to drive the sensor bridge-network. In this scheme the output of the sensor bridge network goes to the low noise amplifier (OPA2376, Texas instruments), the purpose of which is to amplify the low voltage level (~mV) of the sensor output. The output of this amplifier goes to microcontroller (MSP430FG4618, Texas instruments) which has built in ADC. The microcontroller receives amplified analog signal and convert it into digital form. The microcontroller accepts this input voltage converts to a digital value using a 12-bit ADC and compares it with a look-up table which was previously stored in the RAM where the sensor output voltage versus gas-concentration was stored. The digitized value was compared with the closest stored voltage and the corresponding gas-concentration value was displayed. The power consumed by the circuit in ON state is only 36mW. Integrated Development Environment (IDE) called CCSv4 (Code Composer Studio Version 4) is used in order to compile and debug the code required to display the voltage output of sensor bridge networks in the LCD of the microcontroller. The code was written in standard C language. The USB interfaced Flash Emulation Tool (FET) MSP-FET430UIF is used to upload the code into the microcontroller.

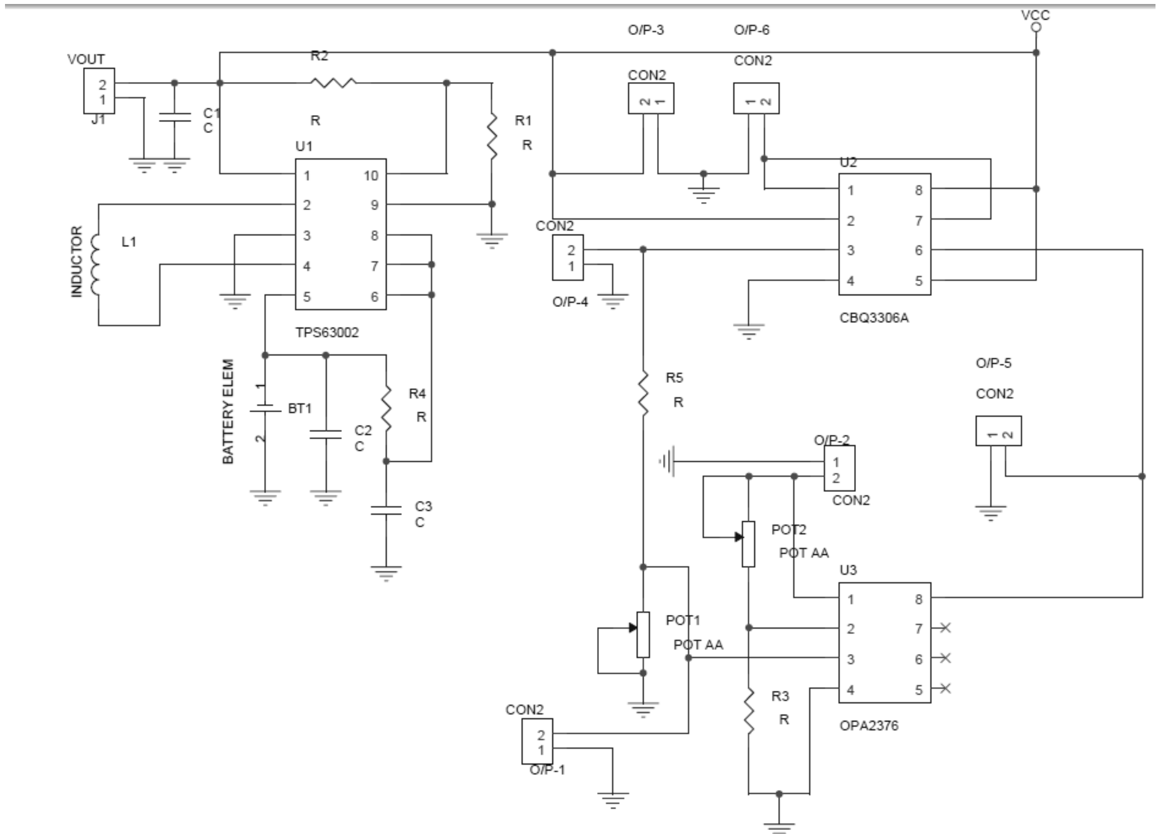
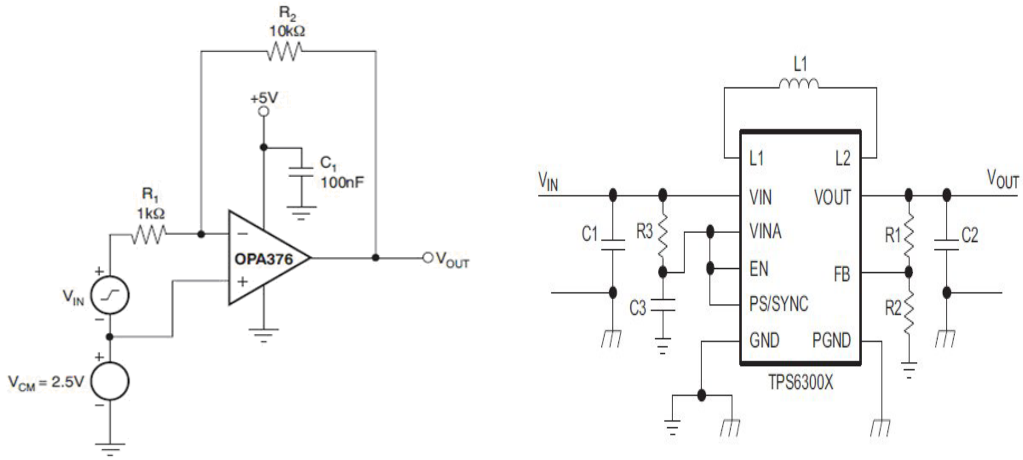


Figure 4. Detail circuit connection for the signal conditioning unit

As shown in the fig. 4, the OPA2376 op-amp chip has been utilized in the scheme as a low noise, low-offset voltage amplifier which amplifies the voltage output of a particular sensor bridge network. It has a single supply operating voltage ranging between 2.5 to 5V, which is particularly suitable in this case as a 3.6V DC battery has been used as power supply in the proposed circuit. Other advantage is due to high values of CMRR, power supply variations effect is minimized.



(a) (b)

Figure 5. (a) Basic amplifier design (b) Power management Chip (TPS-63002) pin-connection diagram

As, mentioned earlier, whenever the user wants to display the gas concentration, microcontroller closes the switch and one can get the corresponding reading on the display screen. A chip (TPS63002, Texas Instruments) is used for the power management purpose and to prevent voltage fluctuations in supply voltage. It has a high efficiency of 96% leading to less amount of overall power dissipation in the circuit. This chip requires an input voltage of 1.8- 3.6V which is provided by external battery & the output of the power management chip is 3.6V which is used to provide constant voltages to other chips. The input of power management chip was a cadmium cell of 3.6V followed by a switch. This power management chip has also built-in protection for over-heating and load disconnect during shutdown.

The standard values of the components used in the design are summarized in table1.

Table1: The standard values used in the circuit

Name of the Component	Symbol	Value used
Inductor	L1	2.2 µHenry.
Capacitor	C1	10 µF 6.3V, 0603, X7R ceramic

Capacitor	C2	2 x 10 µF 6.3V, 0603, X7R ceramic
Capacitor	C3	0.1 µF, X7R ceramic
Resistor	R3	100 Ω
Resistor	R1 and R2	Depending on the output voltage at TPS63002.

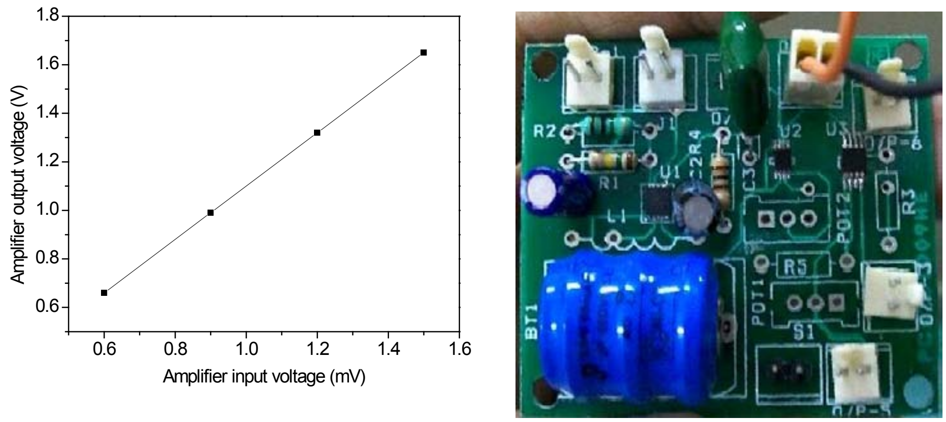


Figure 6. (a) Amplifier output voltage variation as a function of input voltage (b) photograph of developed signal conditioning unit

As revealed from fig 5.(a) the amplifier showed excellent linearity in the desired range with a gain ~ 1.1 in closed loop configuration. For Sensor Bridge output voltage =0.6V,Now by varying the gain of the amplifier we got output voltage in the range from 0.66V to 3.92V. The photograph of the developed circuit is shown in fig 5(b). This hybrid sensor system is very much suitable for detecting a single gas with display of corresponding gas concentrations and subsequent alarming if the threshold limit is crossed due to efficient power management topology used.

VI. CONCLUSIONS

A microcontroller based power efficient signal conditioning circuit for the detection of a single gas using MEMS based sensor has been reported in this paper. The power management was done by judicious use of two switches in such a fashion that circuit only consumes power whenever user attempts to see the gas concentration otherwise it remains in sleep mode consuming negligible power. The power consumption of the MEMS gas sensor is ~ 70mW to 100mW depending upon its operating temperature (150-250°C) and that of entire signal conditioning unit (consisting of low noise amplifier, switch, microcontroller and power management chip) is ~ 36mW in the ON state and only ~7.2µW in OFF state (sleep mode). The test gas in this particular case was methane for which sensor resistance varied from 100KΩ to 10KΩ. The corresponding values of gas concentration were matched form a look up table stored in microcontroller memory. This hybrid sensor system is very much suitable for detecting a single gas with display of corresponding gas concentrations and subsequent alarming if the threshold limit is crossed due to efficient power management topology used.

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