

AC 2008-1533: A COMPUTER CONTROLLED TEST SYSTEM FOR MICRO-ELECTRO-MECHANICAL-RESONATOR (MEMS RESONATOR) GAS SENSORS

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Josh Ward was a senior level Electrical Engineering student at the University of Southern Maine and was working as a Thin Films Process Technician at Fairchild Semiconductor Corporation, S. Portland while working on this project. He will complete his coursework and graduate from U.S.M. with a B.S. degree in Electrical Engineering in May 2008. Upon graduation he expects to be promoted to Process Engineer at Fairchild Semiconductor. Josh's interests are semiconductor device fabrication, CMOS integrated circuit design and automated testing.

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A Computer Controlled Test System for Micro-Electro-Mechanical-Resonator (MEMS Resonator) Gas Sensors

Abstract

This paper describes a computer-controlled test system designed and developed to measure and characterize the response of MEMS Resonator Gas Sensors to various gas mixtures and concentrations and temperature. The change in the resonance frequency of the MEMS resonator due to the absorbed mass of gas molecules on a thin film coating of a polymer layer is being used as a microbalance to measure hazardous gases and volatile compounds. The automated test system developed employs LabView as the software platform for interfacing, communication, data acquisition and control between a personal computer and the test setup via the GPIB bus and the USB and serial ports. The LabView program written controls the injection time of the gas to be sensed, monitors the flow rate, measures and controls the temperature of the chip and monitors and records the frequency of the electro-mechanical oscillations generated in the MEMS resonator. The development of the test system was done by a team of students as a part of their undergraduate senior design projects in electrical engineering at USM.

1. Introduction

The project reported here comprises the design and development of a computer-controlled test system to measure and characterize the responses of MEMS-based resonant sensors to various gas mixtures, concentrations and operating temperatures in an automated way.

“MEMS” is an acronym for “Micro-Electro-Mechanical System”. These devices marry traditional mechanical systems with microelectronics using the silicon semiconductor technology and integrated circuit fabrication. MEMS technology is a natural extension of the integrated circuit technology into the electro-mechanical domain. Engineers use the technique of systematically adding thin films of material on a substrate and then selectively carving portions of those films and the substrate to form both the mechanical structures and electronic components of these devices. This type of process lends itself to the fabrication of electromechanical devices in the micrometer scale with fine features down to the sub-micrometer range. As with semiconductor chip manufacturing, this scale and technology is also conducive to the production of a large number of devices in a batch very economically. ^[1]

Gas sensors are being developed at the Microelectronics Research Labs of Electrical Engineering Department at the University of Southern Maine by employing the principles of operation of MEMS resonators. MEMS Resonators, referred to as “MEMR”s in this document, are microminiaturized electromechanical devices designed to display extremely enhanced mechanical resonance characteristics at a desired frequency. Since these devices can be miniaturized and fabricated on the same chip as an integrated circuit, they are providing an

alternative to the use of a quartz crystal which has been the only device available to design stable oscillator and clock frequency circuits.

Our MEMRs are being specifically developed as gas sensors for applications in sensing hazardous gases and vapors in the environment. Such a resonator consists of a shuttle mass tethered to a substrate with thin beams acting as springs, and a comb drive assembly. **Figure 1** (below left) displays a micrograph of one of the designs. The shuttle is the green square in the center of Figure 1. The comb drives, above and below the shuttle, serves the dual purposes of creating the electromechanical coupling between externally applied voltages and the mechanical motion of the shuttle, as well as sensing the motion of the shuttle.

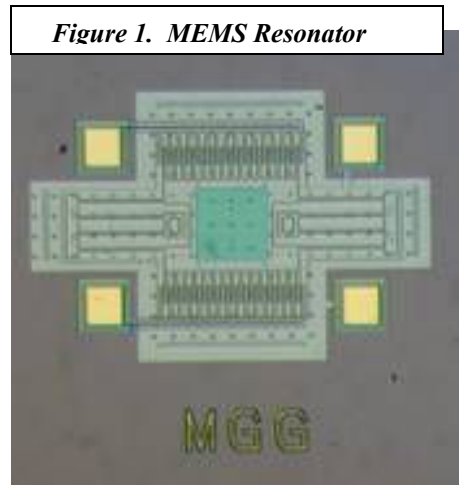


Figure 1. MEMS Resonator

As with any resonator, this system oscillates at a natural frequency determined by the mass of the shuttle and the spring constant of the tethers,

$$2\pi f_r = \sqrt{(k/M)}$$

, where f_r is the resonance frequency, k is the spring constant and M is the mass involved. For gas sensing applications, the shuttle can be coated with a thin film of a polymer with gas absorption properties. Any absorption of gas by the polymer will increase the mass of the system, and therefore, lower the frequency of its resonance. Utilizing polymers with gas specific qualities, it is possible to

calibrate the MEMS resonator for gas detection purposes such that the concentrations can be determined. The process of absorption is a temperature dependent reaction, therefore control or monitoring of the device temperature is important.

For the gas sensing to be effective, the resonance should be well defined with a high “Quality Factor, Q ” at atmospheric pressure. “Quality Factor” is defined as the ratio of the resonance frequency divided by the width of the resonance peak at half power. **Figure 2** is a display of the electromechanical response of one of our MEMS resonators measured at atmospheric pressure using a HP 4194A Spectrum Analyzer. The blue curve represents the phase, and the yellow curve represents the amplitude ratio between the output and the input of the resonator. This device clearly shows a very sharp resonance peak at $f_r = 32.125$ KHz. The Quality Factor of this device determined from the width between the two half-power points (correspond to points -3 dB down from the maximum) measures to be as high as 500. Such a high Q makes this device suitable for use in a stable oscillator circuit as well as for gas sensing applications.

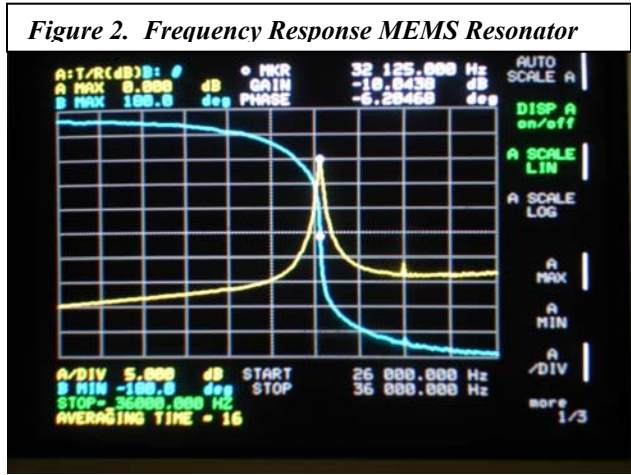
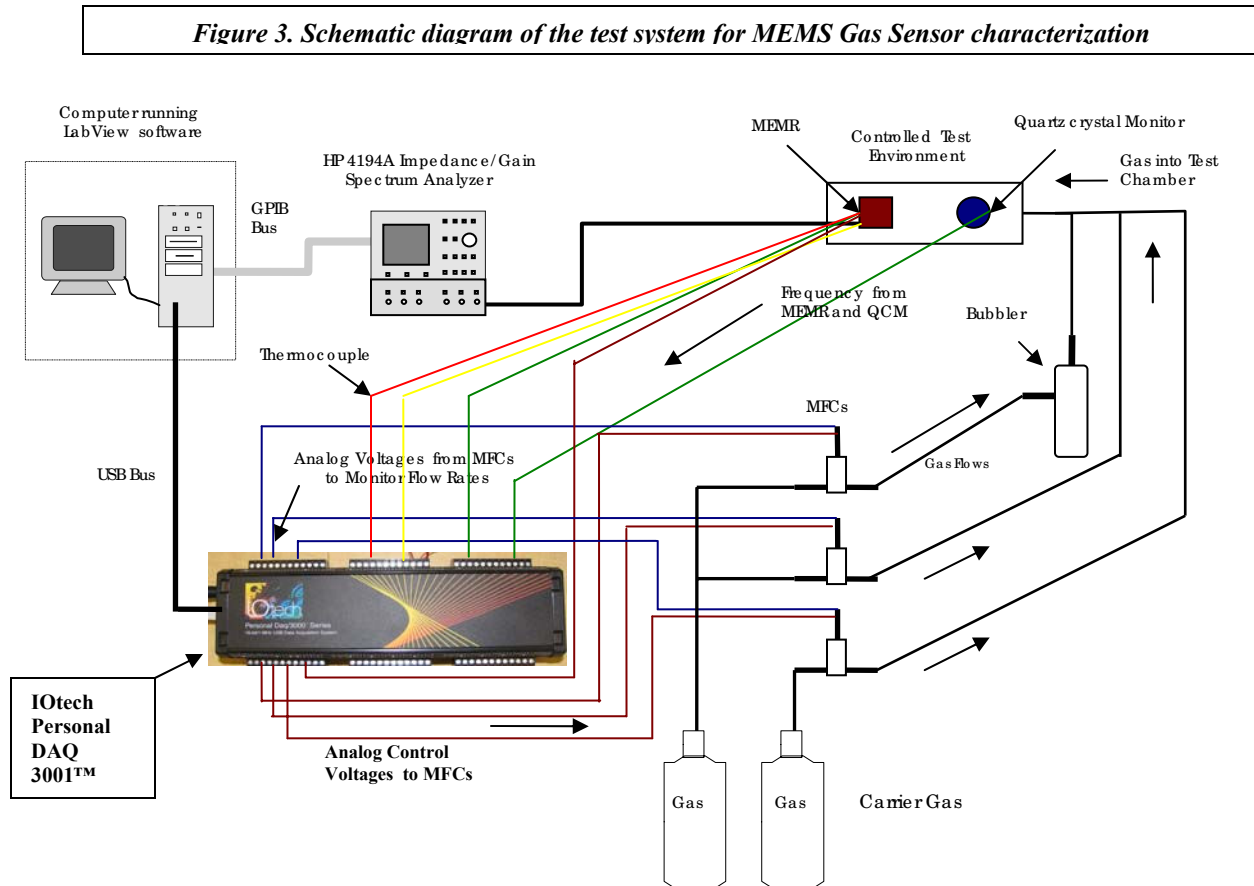


Figure 2. Frequency Response MEMS Resonator

2. Computer Controlled Test System for MEMS Resonator Gas Sensors

The test system we have developed employs LabView as the software platform for interfacing, communication, control and data acquisition between a personal computer and the measurement setup via the GPIB bus, USB and serial ports. Figure 3 gives a schematic representation of the test system.



In order to test the resonator, the gas or the analyte vapor to be sensed is mixed with an inert carrier gas. Mixing of the gas is done to adjust the concentration. The predetermined flow rates, mixtures and concentration levels are computer controlled using a parallel combination of three Tylan, Model FC-260, mass flow controllers (MFCs). The three units are manifolded together via a system of interconnected $\frac{1}{4}$ inch stainless steel tees and plastic tubing, the combined gases then flow via a single line to the test chamber. One of the three lines is used for the carrier gas (Nitrogen or Dry Air) and two are for the analyte gases. The system has the ability to easily connect the two analyte lines to gas bubbler units in order to facilitate the use of a test system that requires a vaporized test gas. The test chamber houses both the MEMS resonator package

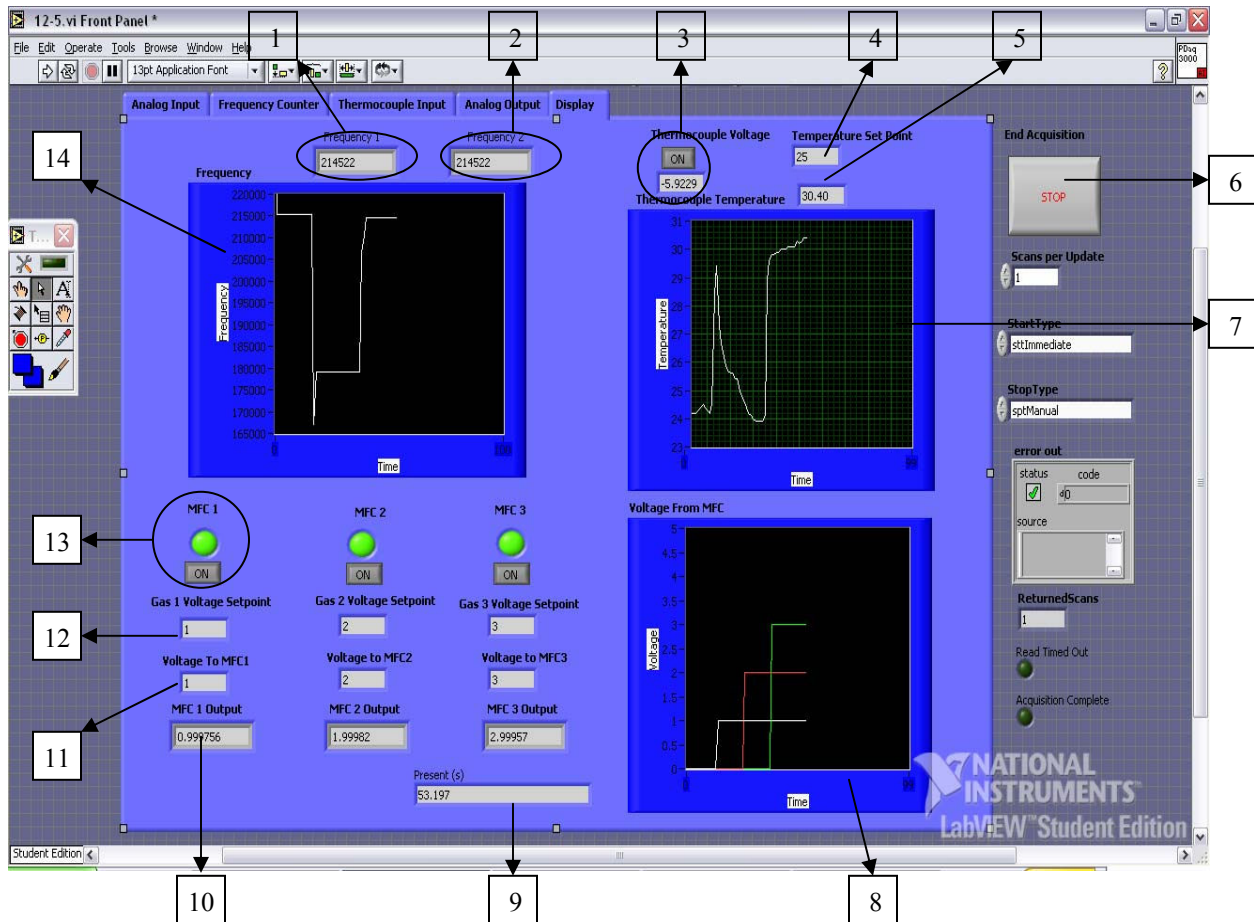
and also a Sycon Quartz Crystal Microbalance (QCM) sensor which is used as reference sensor. The MEMS resonator die is bonded to a 44-pin Chip Carrier and wire-bonded to its terminals. The chip carrier is plugged into a PLCC socket and attached to the chamber, therefore, allowing the wiring to signal processing to remain outside the test chamber and unexposed to the gas mixture. The resonator's electrical output is fed into a trans-impedance amplifier which acts as a current to voltage converter. Voltage amplification and phase angle inversion is done by additional operational amplifier circuits. This signal amplification/phase inversion is needed to bring the closed loop gain of the system to above unity when its output is fed back into the comb drive of the resonator so that self-starting oscillations are obtained to monitor the mechanical resonant frequency of the MEMS structure. This facilitates measurement of the changes taking place in the shuttle mass of the device due to added mass of the gas molecules absorbed.

Central to the computerized control of the project was the data acquisition unit ("DAQ"), the IOtech Personal Daq/3001™. The Daq 3001 is a small portable unit featuring a 16 bit/1 MHz A/D Converter, 16 analog inputs, up to four 16-bit/1 MHz analog outputs, 24 high speed digital input/output channels, two timer outputs and four 32-bit counter. This unit would coordinate and route all the incoming signals from the various aspects of the project to the computer control and back from the computer to the systems via its outputs. Inputs would include the temperature of the package via the input from the thermocouple imbedded in the package and counters for the frequency measurements from both the MEMS resonator and the quartz crystal. Outputs would include power to the heater to maintain the desired temperature setting and voltage to the three mass flow controllers to maintain the desired flow or combination of flows of the gases being tested.

The LabView program written, in addition to the gas mixing ratio, controls the injection time of the analyte and, synchronizes the cycling of sample temperature with purging and gas injection in the test chamber. The program permits variation of both the flow rate and concentration of the gases during a single test cycle, allowing for a dynamic measurement of the sensor response. After each injection the program triggers all measurement instruments and gathers data to quantify and generate plots of sensor response vs. injected gas concentration and temperature. Temperature control and monitoring of the MEMS chip is done with a PID control loop written as part of the master LabView program. This PID control loop uses a thermocouple voltage amplified and outputted as an analog voltage to control the DC power applied to a thin-film-on-ceramic micro heater integrated with the MEMS chip.

Figure 4 shows the LabView window displayed while the system is running. It incorporates both a graphical and digital display of the monitored variables: sensor temperature, the two sensor frequencies measured and the mass flow controller outputs (i.e. flow rates measured). The Labview program also records all data in a user designated spreadsheet file prior to testing.

Figure 4. GUI Window displayed by the LabView control program



- 1) Actual Frequency from the MEMR attached to counter 0 of the Daq 3001
- 2) Actual Frequency from the Quartz Crystal attached to counter 1 of the Daq 3001
- 3) Voltage outputted from PID to heater. ON/OFF button to shut voltage output on or off from DAQ
- 4) Temperature set by user at start-up of the program, temperature the user wants the MEMR to reach
- 5) Actual thermocouple (TC) temperature reading
- 6) When pressed, will first turn all voltage outputs to 0 then stop the program
- 7) Graph of TC temperature over time, which is the temperature of the MEMR device. Graph is set to auto scale. Therefore, a slight difference in temperature will appear large.
- 8) Graph of voltage output from each MFC over time. This voltage can be correlated into the actual gas flow from each MFC.
- 9) Present time, in seconds, from the start-up of the program.
- 10) Actual voltage output from MFC, which can be correlated into the actual gas flow.
- 11) Voltage being outputted from the Daq 3001.
- 12) Voltage set by the user at the start-up of the program.
- 13) LED indicates when the Daq 3001 is outputting a voltage, which causes that specific MFC to start flowing. The ON/OFF button allows the user to shut the voltage OFF or ON to that specific MFC.
- 14) Graph of frequency of both the MEMR device and the Quartz Crystal on same graph.

3. Conclusions and Remarks

The system was built and the LabView programming was done as a part of senior electrical engineering capstone project at the University of Southern Maine. It has been used in the characterization of MEMS Resonator Gas Sensors under different temperature and gas compositions. It is currently being improved by incorporating USB based data acquisition boards to replace some of the expensive GPIB interfaced instruments to reduce the overall cost of the system, and make the system compact and portable. It is the hope of the authors that this system will lend itself to be reproduced and adapted for other uses in laboratories and applications requiring an inexpensive and portable means of computer controlled test systems.

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Acknowledgements

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