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Zero-Net Power, Low-Cost Sensor Platform

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The following article is based on efforts of two divisions and four groups within ESTD. The groups were Sensor and Instrument Research, Monolithic Systems Development, Advanced Lasers, Optics, and Diagnostics Technology, and RF and Microwave Systems and the other contributing division was Environmental Sciences. This project moved us along the path of where sensor systems are headed, which is ultra low-power, wireless microsensor arrays.

Abstract

Numerous national studies and working groups have identified very low-power, low-cost sensors as a critical technology for increasing energy efficiency, reducing waste, and optimizing processes. This research addressed that need by developing an ultra low-power, low-cost sensor platform based on microsensor (MS) arrays that includes MS sensors, very low-power electronics, signal processing, and two-way data communications, all integrated into a single package. MSs were developed to measure carbon dioxide and room occupancy. Advances were made in coatings for detecting carbon dioxide, sensing thermal energy with MSs and capacitive, low-power electronics, robust algorithms were developed for communications within buildings over power lines, and an integrated platform was realized that included gas sensing, temperature, humidity, and room occupancy with on-board communications.

Technical Approach

Microsensor Arrays for Gas Sensing - The sensor chips used in the present studies were fabricated in the Multi-User MEMS Process (MUMPs) at MEMSCAP, Durham, NC. These chips measured 5 mm × 2 mm and contained circular parallel-plate capacitors that could be coated with polymer dielectric material using an ink-jet process. The capacitor plates were made of conductive polycrystalline silicon consisting of a 0.5-µm-thick bottom plate resting on the substrate, a 2-µm air gap that was filled with polymer subsequent to the MEMS fabrication process, and a 2-µm-thick ventilated top plate. The circular capacitor plates were 326 µm in diameter with a 126-µm-diameter central fill hole and had a base capacitance of about 0.3 pF. To minimize the possible flexing of the top plate when the polymer swelled due to absorption of the ethanol or water vapor, the top plate was anchored to the substrate with posts (5 µm square) at approximately 60-µm intervals. The top plate also had an array of 3-µm-square etch holes separated by about 30 µm. These holes were required for removal of a sacrificial silicon dioxide layer during chip fabrication, and also to allow analyte vapors to pass through the top plate to interact with the underlying polymer dielectric material during operation. A heater strip encircled the sensors so that the chip could be maintained at 70C, the optimum operating temperature. Other sensors on the chips included various cantilevers for testing infrared sensing and interdigitated transducers for an alternative chemical readout.

The MEMS sensors coated with the sol-gel mixture responded to CO_2 with a decrease in capacitance, while capacitance increased with humidity pulses. This is explained by the change in polarity of the interacting dielectric material. Unfortunately, the performance of the sensors coated was more variable than desired. The material was also subject to degradation due to the presence of species such as SO_2 and NO_2, though temperature cycling appears to mitigate oxidization and extend the useful lifetime. The sensitivity of the MEMS sensors is more than adequate for sensing CO_2 for ventilation purposes, but more work is needed to produce reproducible sensors. Figure 1 shows the response of 4 MEMS sensors to CO_2 levels.

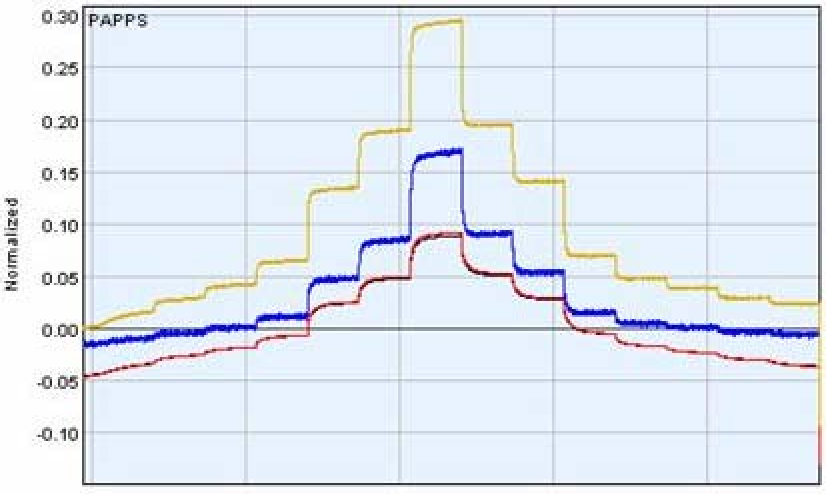

Figure 1. Response of four MEMS Sensors on one chip to CO2.

Microsensor for Detecting Thermal Energy - One of the goals of this LDRD project was to develop micromechanical infrared sensors for use in combination with chemical sensors. To this end during this LDRD project we designed and fabricated several types of geometries that included up to nine different infrared detector designs.

The infrared detectors were suspended bimaterial cantilevers made from polysilicon with a gold layer as the bimaterial layer. These cantilevers detectors were capacitively read using a custom analog ASIC. The noise level was about 10^{-16} farads at a readout rate of 10 KHz.

The detectors were designed to operate in under ambient conditions. A measure of detector performance is the noise equivalent temperature difference (*NETD*). In order for a detector to be able to detect heat from a human a value of *NETD* of 500 mK or better is required. The predicted *NETD* for the designed detectors was about 20 mK in air and less than 5 mK in vacuum. The temperature fluctuation $NETD_{TF}$ is given by

$$NEDT_{TF} = \frac{8\,F^2\,T_d\sqrt{k_B\,B\,G}}{\eta\,A_d\left(\dfrac{dP}{dT}\right)_{8-12\,\mu m}}$$

Where F is the f number of the optics, T_d is the detector temperature, A_d is the detector area k_B is the Boltzmann constant and is photon absorption of the detector.

Although these detectors were expected to detect room temperature objects we were unable, at this time, to detect the heat from a human hand in air or in vacuum. However, these detectors responded to a soldering iron of > 150 C (Figure 2). We expect to achieve detection of room temperature objects even in air by increasing the detector area and eliminating thermo-mechanical noise sources. Designs and new materials have been considered but time and funding did not allow these to be fabricated nor tested. An off-the-shelf IR motion detector was modified to integrate into the system package and this plan was successfully implemented.

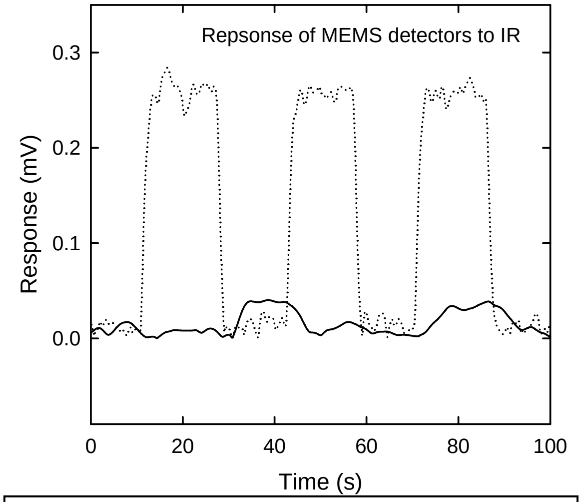

Figure 1. Response of cantilever sensors as a function of time.

Ultra-low Power Electronics - Hardware and software were developed to read various sensors that detect room environmental conditions. The hardware consisted of a circuit board set containing the existing GS2 custom ASIC, a microcontroller to communicate with the host computer via an AC line coupler, and various sensors. The circuit board set included a daughterboard that contains the micro-cantilever sensors and GS2 ASIC, and a motherboard that contained the remaining circuitry.

The GS2 ASIC is a mixed-mode capacitive readout chip that is fabricated in the TSMC 0.35µ process. The GS2 ASIC is a full featured capacitive readout chip with 10 inputs and is fully programmable via a 4-wire SPI interface. The ASIC can drive and sample two micro-cantilever sensors simultaneously. The drive circuit has programmable timing and voltage amplitude. An on-chip average of up to 16 samples is available to increase the noise performance. The sampled values are then converted to a digital value by the on-chip 10-bit SAR ADC. The ASIC also contains a thermometer circuit for sensing chip temperature.

The motherboard contained the remaining sensors and electronics and a socket for inserting the daughterboard. The motion detection circuit, a temperature and humidity sensor, and the micro-cantilever heater control electronics are on the motherboard. It also has the electronics that process the signal from the micro-cantilever Si-RTD. This allows sensing the temperature of the micro-cantilevers. A microcontroller handles external communication and interfaces with the ASIC and other sensor electronics. The microcontroller communicates to the PC via the AC line coupler using a simple 2 wire RS232 serial interface. The circuit boards were designed to work independently of the AC line coupler device. Therefore the boards can be interfaced directly to the computer via the PC serial port. Communication speed was set at 2400 baud for the purpose of interfacing to the AC line coupler. However, reprogramming the microcontroller could increase the speeds to the microcontroller limit of 115000 baud.

LabView software was developed to interface with the microcontroller on the motherboard using the PC serial port. The software allows the user to enter all GS2 configuration data, select the sensors to be read, and the frequency of these readings.
The system data is then collected by the software, displayed on the screen, and saved to the hard drive for further analysis.

The system is capable of reading any of the micro-cantilever sensors, the micro-cantilever temperature, GS2 temperature, ambient temperature & humidity, and any room movement since the last reading. It also has the ability to heat the micro-cantilever device. When tested via direct connection to the PC, the sensor readout system worked very nicely up to 2400 baud. At this communication speed, a complete setup and readout of all sensors was around 7 seconds. No tests were conducted above this speed, but data rates in excess of 115000 baud should be easily achievable. When connected to the PC via the AC line coupler the system worked just as well with the exception of the data readout rate being reduced due to the data overhead of the line coupler.

Robust Communications - The intent of this portion of the LDRD program was to develop and demonstrate a highly energy-efficient sensor interface and spread-spectrum radio-frequency (RF) telemetry unit that would typically be deployed in both new and retrofit installations. The very low-power “plug-in” unit would operate using capacitively coupled energy from the single- or three-phase 60-Hz AC power line. A design for this telemetry was completed. Additionally, a spread-spectrum RF protocol (ORNL invention disclosure in process) was developed that was an outworking of emerging ORNL technology (and two currently pending U. S. Patent applications) to address the difficult signal-propagation environment of a home or building AC power distribution system, which is characterized by very high broadband noise levels (largely from brush-type motors), large transient voltages, and wildly varying RF impedance levels (due to intermittent load switching, local line reflections, and disturbances from neighboring users on the grid). Due to funding constraints, this telemetry design could not be implemented so a survey of lower-performance but commercially available power-line transceiver devices was performed. The most capable one, the IT800D transceiver chip from ITRAN Corporation, was selected for the demo. The IT800D device incorporates a high performance Data Link Layer (DLL) with a Carrier Sense Multiple Access / Collision Avoidance (CSMA/CA) channel access scheme and a robust physical layer (PHY) transmission protocol which has proven effective in many power-line data-transmission applications. Custom software was developed to run the host microprocessor to do the data stream buffering demanded by the IT800D. The software implemented a 256-byte FIFO in on-chip RAM. A full-duplex (simultaneous, bidirectional) communication system to transport the sensor array data to the host computer was thus successfully implemented.

Results and Discussions

Significant progress was made on microsensor technology for gas detection and thermal energy detection. A coating was developed that had the range and sensitivity to measure carbon dioxide for building/office ventilation control, energy optimization, and personnel health. To obtain a reasonable response time the sensor required heating to 70^0C, which is easy to do but this meant the ultra-low power goal had to be compromised. Long term stability remained an issue for further research.

The microsensor research for thermal energy detection led to an increase in the understanding of thermal noise sources and microfabrication issues. A first-of-a-kind capacitive readout thermal cantilever was developed that could detect hot object over 150^0C. Design and materials changes were identified to further increase sensitivity and remain areas for additional research to reach the initial goal of human detection.

Ultra-low power electronics development proceed very well and readout and signal conditioning electronics met all project goals of integrating gas sensing and thermal energy detection with the same capacitive electronics. An algorithm was developed to increase the robustness of signal communications over power lines in buildings and a low-cost line couple was created by modifying off-the-shelf units.

Finally, an integrated platform was developed that simultaneously measured carbon dioxide, humidity, temperature, and room occupancy. The platform also included communications and power delivery from existing power lines. This integrated low-power, multi-sensor array is pictured in Fig 3.

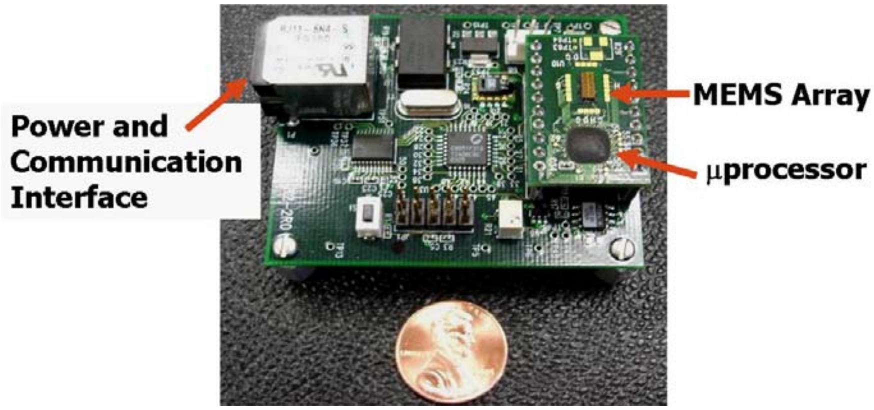

Figure 3. Integrated low-power, multisensor array

Benefits

This project is relevant to DOE in several mission areas including Building Technologies, Industrial Technologies-IOF-Sensors and Controls, and Fossil & Fuel Cell Energy technologies. The zero power, low-cost sensor platform will allow more extensive monitoring of processes as well as environmental conditions for personnel health and comfort. The research into low-power electronics and multi-sensor arrays advance measurement science that is an enabling technology for most DOE programs. This project has applications to Department of Defense programs and Homeland Security programs. Collaborations and proposals have been created with Seacoast Science, Rockwell Scientific, RA Bedell Co., and QUALCOMM. Proposals that include this technology have also been delivered to NASA, DOE, and DHS. One invention disclosure is being filed and two papers were written. At least two more papers will be developed in FY2005.