MEMS Sensors for HVAC&R

Small, Fast, Cheap

By David Yashar and Piotr A. Domanski, Ph.D., Member ASHRAE

Microelectronic mechanical systems (MEMS) have revolutionized the market for sensors by providing small, fast-responding measurement devices at low cost. They have been widely accepted in several common products. As an example, today's automobile uses between 25 and 70 MEMS sensors to gather information where traditional macroscale sensors would be far too expensive to use.[1]

Increasing pressure for improved operating efficiency and reliability of HVAC&R equipment will promote the use of MEMS sensors in comprehensive fault detection and diagnostics (FDD) schemes. The combination of MEMS sensors, FDD, and networking capabilities has the potential to change the way refrigeration and air-conditioning systems are monitored and serviced.

MEMS Overview

MEMS share many of the distinctions of integrated circuits. However, they are considerably different in that they incorporate mechanical devices such as diaphragms, cantilever beams, gears, springs, etc. (see sidebar "The Making of MEMS" on Page 72). The incorporation of these features enabled the production of many MEMS sensors, which supplanted traditional sensors in the automotive, biomedical, aeronautical, and information technology sectors.

Over the past three decades, the global market for MEMS devices has grown to tens of billions of dollars per year.[2] This success is attributed to the low manufacturing cost per part of these devices, their precision, compact size, low weight, and reliability. The small size of MEMS sensors is a significant advantage over its conventional counterparts. It allows MEMS sensors to be used in systems without being intrusive, i.e., fluid properties could be measured without significantly disturbing the fluid, inertial properties can be measured without adding mass, etc. The small size and weight also result in a small thermal capacitance and small inertia of the sensor. Therefore, these sensors exhibit much better temporal response than conventional sensors.

Opportunities for MEMS in HVAC&R

At present, the use of sensors in vapor-compression systems has been limited to traditional and expensive macroscale sensing devices, which are typically used in very large systems where their cost can be absorbed. It is safe to assume that the success of MEMS in other industries will be mirrored in some way in the HVAC&R field, and MEMS sensors will be used increasingly in vapor compression systems.

Some sensors needed to monitor key parameters in a vapor compression system are quite common, and they have already been developed as MEMS devices. For example, different MEMS *temperature sensors* are on the market now, with thin film platinum resistance temperature detectors (RTDs) and thermistors being the prevalent designs. These devices have similar accuracies to their macroscale counterparts. The sensing element is a simple resistor, either of platinum or doped polysilicon, deposited onto a chip. The resistivities of these materials change with temperature. Therefore, the measured resistance can be used to infer the temperature. The cost of MEMS temperature sensors themselves is low, with high volume pricing less than $0.50 per unit, including packaging. For this reason, they are often included onto other MEMS sensors instead of being manufactured as their own entity.

MEMS pressure sensors are fabricated in large-scale production with accuracies in the range of ±1% and a variety of pressure ranges (0 – 5 psi [0 – 34 kPa] to 0 – 5,000 psi [0 – 34 MPa]). This device is easily fabricated by depositing stress sensitive polysilicon resistors (piezoresistors) onto a thin diaphragm. As pressure is applied, the diaphragm flexes and strains the piezoresistors located on its surface. The amount of flexure of the diaphragm is detected by measuring the change in resistance of the piezoresistors. This is the most common type of pressure sensor, as its fabrication is rather simple and the operating ranges are quite flexible. The cost of such a device varies widely with the scale of production. For large volume, typical pricing for MEMS-based pressure sensors is in the $20 to $30 range, with the majority of the cost being attributed to the rugged packaging of the device. A number of vendors also provide individual dies, leaving the packaging up to the user. These may be obtained for price under $0.40 per unit.

Many MEMS *humidity sensors* have been developed and some are commercially available.[3] The capacitive humidity sensors are the most common type. These sensors consist of a porous dielectric material placed between two parallel capacitor plates. When exposed to a humid environment, this material absorbs moisture, which changes its dielectric constant. Therefore, the level of moisture is indicated by the capacitance measured between the parallel plates. Humidity sensors of this type typically are priced between $15 and $85, depending on the quantity and type of packaging.

Vibration sensors can be used for early detection of compressor and fan problems. A departure from its normal vibration signature may indicate a potential problem with the system. A basic, inexpensive design for a vibration sensor can be as simple as a cantilever beam fabricated on a chip. Such a device is being studied at the National Institute of Standards and Technology (NIST).[4] When the chip is subjected to vertical acceleration, the cantilever will bend. Information regarding the amount of bending is acquired by measuring the resistance of a piezoresistor deposited onto the base of the cantilever. *Figure1* shows a photograph of the device under study.

More complicated types of MEMS motion sensors are available, and they can be sized to measure compressor and fan vibrations. Traverse vibrations can be measured using accelerometers, similar to those used to control automotive air bags (commercially available from $4 to $20). These devices work by stabilizing a proof mass suspended in a fixed location with springs. *Figure 2* shows a sketch of a typical lateral acceleration sensor. The proof mass moves relative to the anchored chip when the chip is subject to a change in velocity. The sensing mechanism for such a device typically is capacitive. Therefore, the measured capacitance between the two features is a function of the distance between them.

Viscosity sensors can indicate the condition of the refrigerant/lubricant mixture in the system and can enable condition-based maintenance. Macroscale viscosity sensors include capillary, float viscometers, falling-ball, vibrating reed, and quartz oscillator viscometers. None of these sensors could be used in most compressors because their size conflicts with the space limitations and the available amount of lubricant required for sensing. For several years now, researchers have been pursuing a feasible design of a MEMS viscosity-measuring device.[5] The recent exploratory evaluation of a microresonator, SAW (surface acoustic wave), and FPW (flexural plate wave) sensors indicated the FPW device to be most promising for the 1 cP to 15 cP (1 mPa·s to 15 mPa·s) viscosity range of a lubricant in the refrigeration compressor.[6]

FPW devices operate by generating a flexural wave that travels along a thin membrane. Since the flexural wave is slower than the speed of sound in the fluidic medium, the wave is confined to the plate rather than dissipating into the liquid. The viscosity of the medium can be inferred from the frequency

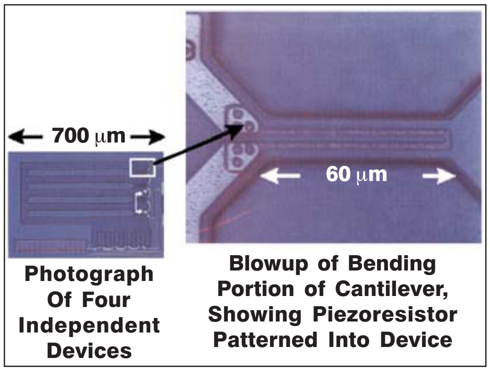

Figure 1: Photograph of antilever beam vertical accelerometer.

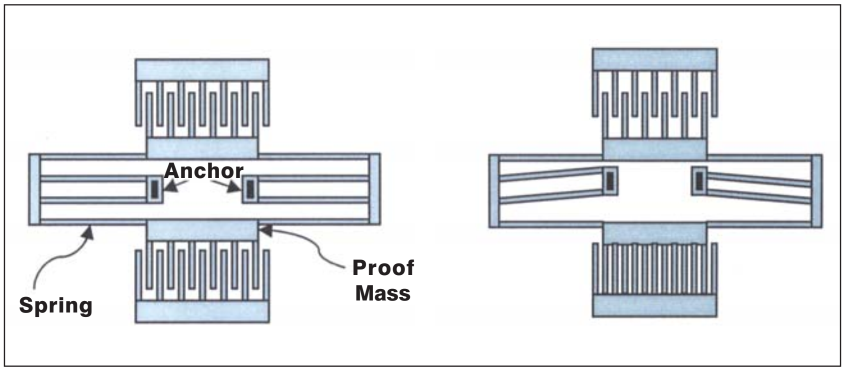

Figure 2: Typical design for a lateral acceleration sensor.

and attenuation of the waves. This device is shown in *Figure 3.* FPW devices offer as much as a 20-fold reduction in the size of the sensor with an ultimate target price of $8 per unit.

ISFETs or CHEMFETs (ion sensitive field-effect transistors or chemical field effect transistors) can be used to monitor pH or to detect contaminants indicating undesired chemistry occurring in the refrigerant/lubricant mixture. The primer provided on the Web site by Sentron[7] provides a detailed description of how these devices operate.

Flow velocity sensors could provide refrigerant mass flow rate, and condenser and evaporator air-side or water-side flow rates, which are very important parameters. Most MEMS flow sensors are still in the experimental stage. Only gaseous flow sensing has been addressed as all of the research in this area has been driven by the aeronautical industry. Currently, anemometers and boundary layer shear stress sensors have been developed.[8] Due to the inherent small size of MEMS sensors, no direct method of macroscale flow measurement is pos-

The Making of MEMS

The structures that make up MEMS devices are formed through our ability to micromachine silicon and other materials on the milli- to microscale (10^{-3} m to 10^{-6} m) using processes developed within the electronics industry. It is through these processes that we are able to build, grow, carve, and piece together small features that can be integrated into devices capable of performing specific tasks.

At the heart of the silicon processing industry is the ability to produce large quantities of devices through batch fabrication. These devices are manufactured simultaneously by performing a set of process steps on a silicon wafer. After the processes have been completed, the wafer is the cut into small sections, called dice, each containing an individual device. The wafers range in size from 50 mm (2 in.) to 450 mm (16 in.) in diameter. Typically, the smaller 50 – 100 mm wafers are used for research purposes, while larger wafers are used for the mass production. The required processes can often be costly; however, the cost is absorbed by the large number of dice on a wafer. As a result, the cost of an individual device is low when very large quantities are produced.

The most commonly used processes include photolithography, surface and bulk micromachining, and bonding. Photolithography is the most important process at our disposal. It is the process by which a pattern can be transferred to a wafer through the use of light and light sensitive materials. The basic process is hundreds of years old. It requires a light source, a mask (an object consisting of transparent and opaque sections), and a material with sensitivity to light. For advanced processing, a particular wavelength of light is shone through a mask onto a wafer coated with a light sensitive polymer called a photoresist. Once a photoresist has been exposed to this light, it becomes weaker than unexposed photoresist and may be preferentially removed.

Surface micromachining is the removal and addition of thin layers of material through thin film etching and deposition. Bulk micromachining is the removal of large, deep sections of material. It is performed by exposing the material to a reactive liquid, gas, or plasma. It can be performed isotropically or preferentially in certain directions (anisotropic). Anisotropic etching is commonly performed in such a way as to preferentially remove silicon atoms in a crystal lattice based on their orientation in the lattice; the result of this is surfaces whose smoothness approaches perfection at the atomic level. Plasma etching techniques which allow anisotropic line-of-sight etching are also frequently used.

Various material layers (metals, nitrides, oxides, and polymers) can easily be deposited onto a wafer. Also, impurities may be introduced into silicon, through various implantation and diffusion methods, to selectively and locally alter the mechanical and electrical properties of the silicon. Another material that is commonly used is the naturally occurring oxide formed on silicon, (SiO_2). Silicon dioxide has different mechanical, electrical, chemical and thermal properties than silicon, and it is easily formed on and removed from silicon.

Bonding is also a very important process for MEMS manufacturing. Without the ability to bond, building complicated three dimensional features would often be impossible. Bonding allows an engineer to build different parts of a device on different dice and bond them together to form a more complicated device.

The combinations of these processes (and many others that are much more specific) allow production of different microscopic features needed for building a MEMS device with desired functionalities.

sible. However, for some applications, the information tendered by these measurements can be useful. Anemometers work by adding heat to the flow using a small heating element at the boundary. The amount of heat added to the flow through convection is measured and is used as an indication of the flow velocity. A shear stress sensor is placed on a flow boundary. It measures the amount of shear force imposed on a boundary from the flow, typically using a floating element sensor that is elastically held in a location.[9]

Pressure drop (differential pressure) sensors can be applied to air, water, or liquid line filters. These sensors are similar in many ways to the pressure sensors described previously. The difference being that they reference opposing sides of the chip rather than a vacuum. They are packaged with small capillary tubes on both sides of the sensor and may be installed with the capillary tubes extending to the two pressure ports on each side of the filter. Reaching a predetermined level of pressure drop would indicate the optimal time to change the filter. MEMS differential pressure sensors also can be used for detection of frost buildup and defrost cycle initiation. Measuring the air-side pressure drop would be a much more direct way of determining when to initiate a defrost cycle.

Concluding Remarks

It is certain that the success MEMS devices have had in other fields will be repeated in some way within the HVAC&R industry. The drivers for implementation of MEMS sensors are their dropping cost and improved functionalities and the growing awareness of the benefits that can be obtained from system monitoring and comprehensive FDD schemes.

At present, the benefits of FDD schemes are not fully characterized, and a current research project initiated by ASHRAE Technical Committee 7.5[10] will provide the needed information. Independent surveys indicate that the impact of FDD can be substantial. One independent survey of 1,500 rooftop units showed that the average efficiency was only 80% of the expected value, mostly due to improper refrigerant charge.[11] In a different survey of more than 55,000 residential and commercial units, the refrigerant charge was found to be incorrect in more than 60% of the systems.[12]

Breuker and Braun[13] have shown that improper refrigerant charge and four other common faults can be diagnosed using as little as five absolute temperature and two differential temperature measurements. Measuring other parameters enhances FDD capabilities. More comprehensive FDD schemes addressing equipment reliability will involve vibration and viscosity sensors, and may be used in value-critical applications in which equipment failure is intolerable due to expensive cargo or equipment cost.

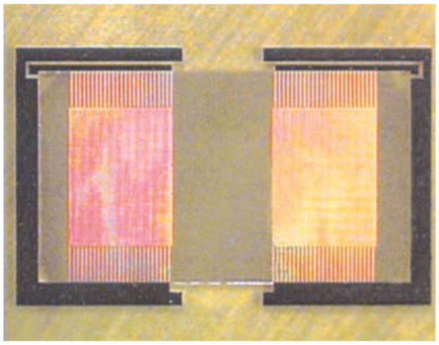

Figure 3: Flexural plate wave sensor, from Boston Microsystems used with permission.

Looking further into the future, the combination of MEMS sensors, FDD methods, and networking capabilities will change how refrigeration and air-conditioning systems are serviced. For example, remote monitoring, which is now available for large building systems, could be applied to residential air conditioners. The current practice of a pre-season walk-through inspection of an entire community could be changed to responsive maintenance based on fault signals conveyed electronically to the maintenance staff. Ultimately, the vision for future HVAC&R equipment is that it will be more efficient, more reliable, and smarter. MEMS technology holds one of the keys to this vision.

Advertisement in the print edition formerly in this space.

Acknowledgments

Support was provided by the U.S. Department of Energy, Building Technologies Program, Contract Number DE-AI01-97EE23774; Arun Vohra, manager.

Notes

This article is a contribution of the National Institute for Standards and Technology (federal government) and is not subject to copyright.

References

1. Freiburghouse, A. 2001. "The MEMS microcosm: transportation." *Forbes*, April 2, www.forbes.com/asap/2001/0402/051.html.

2. Grace, R.H. 2003. *Commercialization Issues of MEMS/MST/Micromachines: An Updated Industry Report Card on the Barriers to Commercialization.* NSF Nanotechnology Manufacturing Workshop, Birmingham, Ala. Jan. 5. www.nano.neu.edu/pdf/NSF_Workshop_pdf/Grace_RogerGraceAssociates.pdf

3. Rittersma, Z.M. 2002. "Recent achievements in miniaturized humidity sensors — a review of transduction techniques." *Sensors and Actuators* A96. pp.196–207.

4. Payne, W.V. 2004. Personal communication. National Institute of Standards and Technology, Gaithersburg, Md.

5. Martin, B.A., S.W. Wenzel, and R.M. White. 1990. "Viscosity and density sensing with ultrasonic plate waves." *Sensors and Actuators* A21–A23. pp.704–708.

6. Chan, J. 2003. Private communication. Boston Microsystems, Inc., Woburn, Mass.

7. Sentron, Integrated Sensor Technology. 2003. *General Information about ISFET Technology*. www.sentron.nl/index.php?iRubrikID=4218&exthov=0311100206.

8. Breuer, K. 2000. *MEMS Sensors for Aerodynamic Applications — the Good, the Bad (and the Ugly*). AIAA 2000-0251, 38th Aerospace Sciences Meeting & Exhibition, Reno.

9. Padmanabhan, A. 1997. *Silicon Micromachined Sensors and Sensor Arrays for Shear-Stress Measurements in Aerodynamic Flows*. Ph.D. Thesis, Department of Mechanical Engineering, Massachusetts Institute of Technology, Cambridge, Mass. http://raphael.mit.edu/Technical_Reports/Padmanabhan_Thesis.pdf.

10. ASHRAE. 2004. "Field performance assessment of package equipment to quantify the benefits of proper service (1274-TRP)." Research Project, TC 7.5, Smart Building Systems.

11. Rossi, T. 2004. Personal communication. Field Diagnostic Services, Inc. Langhorn, Pa.

12. Proctor, J. 2004. "Residential and small commercial central air conditioning; rated efficiency isn't automatic." Presentation at the Public Session. ASHRAE Winter Meeting, Anaheim Calif. Jan. 26.

13. Breuker, M.S. and J.E. Braun. 1998. "Common faults and their impacts for rooftop air conditioners." *International Journal of HVAC&R Research*. 4(3):303–318.

David Yashar is a mechanical engineer, and Piotr A. Domanski, Ph.D., is a group leader for the HVAC&R Equipment Performance Group, National Institute for Standards and Technology, Gaithersburg, Md.