Application of MEMS Technology in Automotive Sensors and Actuators

DAVID S. EDDY AND DOUGLAS R. SPARKS

Invited Paper

Sensors and actuators are the critical system components that collect and act on information in the analog environment and link it to the world of digital electronics. The functional groups of sensors, software, controller hardware, and actuators form the backbone of present and future automotive systems. Unit volumes for sensors and actuators in the automotive industry are measured in millions per year and at a unit cost of a few dollars. The design of sensors and actuators has increasingly made use of microelectromechanical systems (MEMS) technology. This technology is well suited to producing a class of micromachined sensors and actuators that combines signal processing and communications on a single silicon chip or contained within the same package. This paper contains a discussion of the issues in producing MEMS sensors and actuators from the concept selection stage to the manufacturing platform. Examples of commercial and emerging automotive sensors and actuators are given, which illustrate the various aspects of device development. Future trends in MEMS technology as applied to automotive components are also discussed.

Keywords— *Accelerometers, actuators, automotive systems, gyros, microelectromechanical systems, micromachines, pressure sensors, sensors.*

I. INTRODUCTION

Sensors and actuators are components of automotive electronic control systems. Hence, the types of sensors and actuators required are dictated by the desired control system function. A simple partitioning of an automotive system is shown in Fig. 1. There are basically four blocks: 1) sensors, 2) software, 3) controller hardware, and 4) actuators. All of these functional blocks work together to achieve the desired control results. Further, all of the system components must be low in cost and manufacturable in high-volume operations.

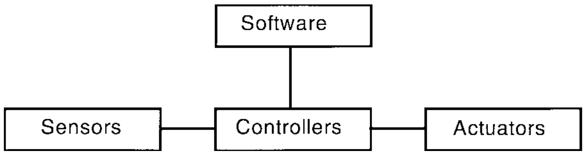

Fig. 1. Functional partitioning of automotive systems.

The types of automotive systems currently found on most modern vehicles are those that control engine, powertrain, suspension, and braking, along with utility systems that control the vehicle body functions, and information systems for communication within the vehicle as well as externally.

Since about 1980, there has been an ever increasing penetration of electronic control systems and electrical components in automotive products. In general terms, these systems can be categorized into the areas of powertrain and chassis control, comfort and convenience, and communications. Each of these systems requires an application-specific set of low-cost sensors and actuators to make the system application viable.

II. HISTORICAL PERSPECTIVE

Starting in 1979, the microprocessor-based automotive engine control module was phased in to control the engine air-to-fuel ratio fixed at the stoiciometric point. By doing this, the catalytic converter efficiently minimizes the tailpipe emissions, bringing them into compliance with federal regulations. With these engine control systems came the need for sensors on both the input and exhaust sides of the engine. The exhaust oxygen sensor filled the need on the exhaust side, giving a step function feedback signal at the air-to-fuel ratio stoichiometric point. A manifold absolute pressure (MAP) and a manifold air temperature (MAT) sensor were used to compute the density of air entering the engine. The product of air density and engine speed gave the mass of air entering the engine.

Historically, it was this automotive system, requiring a MAP sensor, that introduced the microelectromechanical systems (MEMS) technology to the auto industry in high volume units. While competitive sensor technologies could satisfy the MAP sensor requirements, a silicon-micromachined pressure sensor became the device of choice

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D. S. Eddy is with General Motors Global Research and Development Operations, Warren, MI 48090 USA.

D. R. Sparks is with Delphi Delco Electronics Systems, Kokomo, IN 46904 USA.

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due to lower cost and smaller size. As it turned out, both the Delco Electronics Division of the General Motors Corporation and the Ford Motor Company developed similar approaches in applying the MEMS technology. Delco Electronics developed the MAP sensor using a piezoresistive principal and bulk micromachining of silicon [1]–[4]. Ford also used a bulk-micromachining approach but used a capacitive measurement principle [5], [6]. Today, the volumes of MAP sensors continue to grow and are measured in millions of units per year, matching the total volume of cars and trucks produced by the automotive industry each year. Further, newer versions of these MAP sensor devices have been designed, which take advantage of the advances in the MEMS processing technology.

A similar scenario was played out in the mid-1990's, when air-bag restraint systems were introduced. Non-MEMS, ball-in-tube acceleration sensors were used for relatively high-cost, inflatable restraint systems when these were vehicle options. When mandated, the need for a lower cost motion sensor became apparent. Micromachined accelerometers were able to fill this need, and are replacing most original sensing technologies in the automobile [7]–[10].

Most of the commercial automotive activity for MEMS technology has been in the sensors area. Actuators having MEMS parts are starting to emerge as ways to fabricate intricate parts.

III. MARKET FORCES

Along with the system input, requirements for high-volume, low-cost advanced technology often provide the driving force for a new MEMS product. Smaller size, along with the required reliability, are other features a microsystem can often use to insure its implementation. Using silicon wafer manufacturing techniques, micromachined devices can often be produced in large batches, at low cost, and at high reliability, and as a result are employed by millions of automobiles.

IV. FUNDAMENTALS

As expected, there are many technical issues that are faced when designing and developing sensors and actuators for automotive system applications. In spite of the very diverse menu of technologies used in automotive sensors and actuators, a particular sensor or actuator technology can be partitioned into a number of parts:

i) an overall principle of operation;
ii) device modeling;
iii) a materials technology system;
iv) a packaging and interconnection system;
v) a manufacturing system for high volume production.

Because of the multifaceted nature of sensor and actuator development, these aspects must be addressed globally in a common design at the start of development rather than summing the individual parts at the end. Too often, substantial effort is put into developing a device concept only to find later that the device is difficult or expensive to package suitably in the automotive environment. In some cases, the cost of materials, processing, and manufacturing make the sensor or actuator device impractical for automotive application. The point to emphasize is that a successful automotive device technology is one that manages the proper balance between these interacting aspects of sensor and actuator technology while simultaneously achieving high device performance at low unit cost. Further, the probability of developing a new device technology is enhanced when consideration of the existing manufacturing infrastructure is taken into consideration when the device concept is selected. It is much easier to bring a device technology into production when all that is needed is a modification of an existing manufacturing process.

V. IMPORTANT LESSONS LEARNED

From past experience in designing and manufacturing automotive sensors, several lessons have been learned that address the issues that must be considered for high-volume automotive applications. They are summarized as follows.

A. Overall Principle of Operation

Simple, robust sensor concepts are preferred for high-volume automotive sensors. High signal-to-noise ratio is a must for the automotive system.

B. Device Modeling

Analytical and computer-aided design (CAD) modeling techniques should be used to determine whether the sensor concept has the parameters (sensitivity, bandwidth, etc.) to fulfill the system requirements. Further, all possible sources of sensor error should be modeled and used to develop compensation methods where needed.

C. Materials Technology System

With MEMS technology, compatibility with the materials and operations in a production silicon integrated circuit (IC) foundry is the major issue. Hence, the MEMS materials are typically restricted to those used in the IC process. Process partitioning can be used as a means of solving the compatibility problem.

D. Packaging and Interconnection System

Packaging operations account for the largest fraction of sensor cost [11]. This is due to one-at-a-time packaging operations using highly specialized production equipment and end-of-line testing and calibration operations. Further, the package structure needs to be modeled concurrently with concept modeling to determine if there are any package-induced error sources, while protecting the sensor from the environment. Also, in automotive sensors, a minimum number (usually no more than three) of wires connecting the sensor to the system is usually a requirement in order to keep the sensor cost low.

E. Manufacturing System for High-Volume Production

While not always possible, a low-cost product can be obtained by employing production-proven techniques utilizing existing manufacturing equipment in order to minimize both development cost and time. One of the major capital investments in any sensor technology lies in the equipment needed to do automated packaging. For high-volume production, this equipment is highly specialized and needs a large plant floor area. It is this aspect of production that comes into play when the next-generation sensors and new sensors are developed. Many times, the manufacturing system has a direct bearing on the sensor concept selection process.

VI. POPULAR SENSOR CONCEPTS

Piezoresistance is one of the most commonly employed micromachining transduction phenomena. The piezoresistive effect is the change in electrical resistance of a material in response to mechanical strain. The gauge factor of piezoresistive elements depends on material, grain size (for polycrystalline materials), doping level, crystallographic orientation, and temperature [12], [13]. Single-crystal P-type resistors, formed in (100) wafers along the $\langle 110 \rangle$ direction, are known to have the highest gauge factor of common piezoresistive material [12]–[14]. The piezoresistive effect in single-crystal silicon has been known since 1954 [15]. Kanda [12] has explained the high sensitivity of single-crystal silicon piezoresistors using a carrier-transfer mechanism and the effective mass change associated with the k-space energy surfaces. Since CMOS and bipolar integrated circuits are fabricated from (100) silicon wafers, this transduction principle was adopted by the first microsystems. Piezoresistive devices have been and still are currently employed in millions of micromachined pressure sensors, accelerometers, and flow sensors [1]–[4], [7], [8].

Capacitance variation is another popular concept used in MEMS sensors. Using a combination of processing methods, a MEMS structure is fabricated to form a capacitor structure on a silicon chip. One of the capacitor plates is exposed to the parameter to be measured and moves relative to the fixed plate. In the case of pressure sensors, a micromachined diaphragm bends relative to the fixed plate, thus giving a capacitance variation as a function of pressure over the diaphragm. Signal conditioning circuitry detects this capacitance variation and converts it to a high-level signal at the sensor output. Further, electrostatic force-rebalance measurement techniques can be used effectively with capacitive sensors.

VII. MODELING TECHNIQUES

In many ways, computer modeling of MEMS is similar to that of integrated circuits. However, unlike IC's, both sensors and actuators must interact with their environments and often utilize moving parts. Interactions with the microsystem's environment may require predictions of fluid flow or the effect of thermal expansion coefficient differences between materials used to house the micromachine. Motion sensors such as accelerometers and angular rate sensors often move, or at least push against, an electrostatic field if used in the force-rebalance mode. Pressure sensor diaphragms bend in response to pressure changes. Relays close and open as do valves. These represent some of the unique MEMS features that are often modeled.

Mechanical modeling is often first employed when designing a micromachined device. Traditional mechanical computer modeling software such as ANSYS [16], ABAQUSCS, or NASTRAN is used, as are MEMS-specific programs such as IntelliCAD, Anise, MEMCAD, and SENSIM [17]–[19]. Mechanical modeling is utilized to determine the structural stability of a device as well as to determine the resonant frequency and response to stress. Placement of transducer elements can be optimized with this type of analysis. Prediction of transducer sensitivity, breakage, and susceptibility to mechanical shock and vibration can also be assessed in this manner.

Flow sensors, nozzles, and valves interact with their surroundings directly and can also be modeled using programs such as FLOTRAN [16]. As in the case of other microdevices, performance, transducer sensitivity, breakage, and turbulence prevention can be better understood early on in the development cycle with computer modeling. Fluid damping is very important in the design of accelerometers, and so models have been developed for this application as well [20].

Once a general micromachine structural model is complete, fabrication simulation can be undertaken. With silicon-based microsystems, traditional IC simulation programs are most often employed. These programs would include SUPREM [21], DAVINCI, and PEPPER to determine the initial oxidation, diffusion, implant, and epitaxial parameters needed to form etch stops, diaphragm thickness, piezoresistors, and other semiconductor and micromachine elements.

As in the case of integrated circuits, the process fabrication model can be linked to the electrical model of any circuit elements used by the microdevice. Just as IC simulation programs have been linked together, MEMS simulation software that joins mechanical process and electrical design has also been developed [17]–[19]. Extensive experimental work is required to optimize the accuracy of any model with results obtained in the factory. Uncalibrated modeling is useful for first-order development; however, confidence in any simulation package is only obtained with verification.

VIII. PROCESS DESIGN

Ideally, process modeling would be the first step in coming up with a MEMS wafer-fabrication sequence. Practically, most MEMS processes start with an existing IC or micromachine process. This is done to save time and development costs and to insure reliability.

The piezoresistive pressure sensor processes used in the late 1970's were derivatives of the bipolar IC processes used at that time. The P^+ piezoresistor layer came from the transistor base process, the N-type epitaxial layer came

Table 1 The Automotive Environment

Temperature:	-40°C to 85°C driver interior, 125°C under the hood, 150°C on the engine, 200-600°C in the exhaust and combustion areas.
Mechanical shock:	3000g during assembly (drop test), 50-500g on the vehicle
Mechanical vibration:	15g, 100Hz to 2Khz
Electromagnetic Impulses:	100 to 200 volts/meter
Exposure to:	Humidity, salt spray, in some applications fuel, oil, brake fluid, transmission fluid, ethylene glycol, freon, or exhaust gases.

from the transistor collector process, and any N^+ substrate tie came from the bipolar emitter process. In some cases, even the P^+ etch stop was derived from top-side/bottom-side junction-isolation P^+ buried-layer process modules. Metal and passivation layers were also borrowed from existing bipolar process flows. Twenty years ago, process modeling was rarely employed, and processing experiments were used to adjust these existing bipolar IC processes into a manufacturable micromachining fabrication sequence. Most original work was required in the areas of silicon etching [22]–[26], wafer bonding [27], and micromachine packaging [28]–[32].

In a similar manner, most piezoresistive accelerometers were derived from already existing micromachined pressure sensor processes. Silicon doping, photolithography, oxidation, and etch processes were used virtually unchanged. In developing this new device, the process modeling utilized was widely available [21]. Plasma or dry silicon etching was required to produce accelerometers, but again, this had already been developed for IC manufacturing [33]–[35]. Other capacitive accelerometers borrowed from conventional CMOS or BICMOS processing in the same way [10].

Radically new micromachined devices will still use existing IC and MEMS processes; however, they will rely more and more on computer modeling for quick implementation. This is especially true of items such as flow sensors, valves, nozzles, and ultrasonic and optical microdevices.

IX. PACKAGE ISSUES

The packaging of automotive MEMS must begin with a consideration of the environment to which the microsystem will be exposed. Table 1 gives the conditions to which an automotive component is subject.

Standardized testing of automotive MEMS components is partially covered in the Society of Automotive Engineers and the military via SAE J1221, SAE J575G, and Military Standard 750. These standards detail accelerated testing procedures such as high and low temperature storage, temperature cycling, and thermal shock that are used in qualification testing of a packaged device. Specific sensors and actuators also have additional reliability testing.

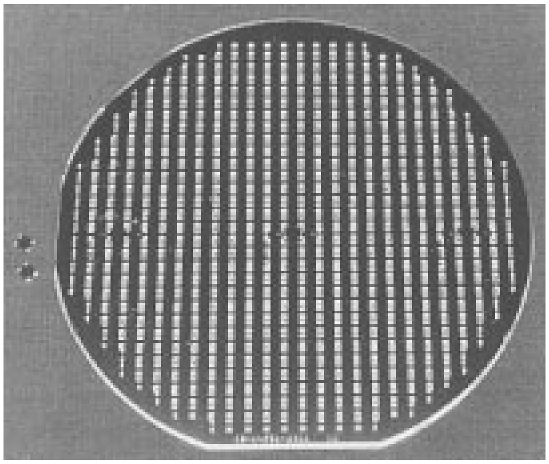

Fig. 2. Wafer-to-wafer bonded micromachines.

As an example, pressure sensors are tested using pulsed pressure and temperature cycling while powered up. Actuators will have similar accelerated actuation testing. These extensive tests are required to insure that a component will function over the five to ten year, or 100 000–150 000 mile, lifetime of an automobile in desert, tropical, and/or arctic locations. Commercial truck components require ten years or 1 million miles of problem-free use.

To be an effective sensor or actuator requires interacting with the environment. To protect a micromachined or electronic element from such aggressive automotive surroundings requires special attention to packaging. Protection starts at the die level. The same types of silicon nitride and doped oxide passivations used to prevent ionic contamination in integrated circuits are employed to protect most microsystem chips. Additional coatings such as parylene or passivating gels are next used to protect the circuit side of micromachined device [28]. Chip-level encapsulation is also used by several types of micromachined sensors such as accelerometers and angular rate sensors to protect moving structures [7], [8], [36]. Chip-level packaging is accomplished by wafer-to-wafer bonding using a micromachined top cap, as shown in Fig. 2. In this capped slice, a cavity is etched to accommodate the moving element, and through-holes are machined above the position of the bond pads to allow for wire bonding of the completed stacked die. Since bonding can be done in a clean room, this type of wafer-level packaging is also an excellent method of keeping particles away for micromachined elements. Particles can lead to shorts or stop element motion. Fig. 3 illustrates how the micromachined sensor is enclosed at the chip level.

Mechanical package design is the next level of protection for a microsystem. Hermetic packaging of the top side of a differential pressure sensor can be used. For lower cost, well-sealed plastic packages can be used in conjunction with gel and/or chip-level packaging [7], [8]. Solder sealing of motion sensors using ceramic side brazed packages has also been employed to produce reliable devices [30]. The

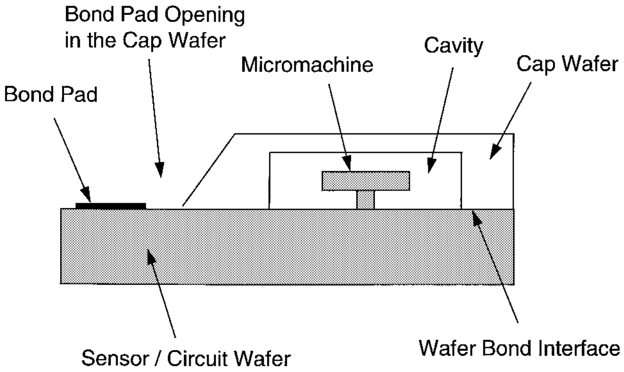

Fig. 3. A cross-sectional view of a chip-level packaged micromachined sensor.

Table 2 MEMS Material Properties

Material	CTE (ppm/K)	Young's Modulus (MPa)	Poisson's Ratio
Silicon	1.8 to 3.2	162,000	0.28
Silicone RTV	800	6.9	0.4
Pb37-Sn63 Solder	28	23,000	0.4
7740 Glass	3.3	62,784	0.2
Alumina	5.1 to 7.5	276,000	0.23
FR-4	15	18,200	0.25
Kovar	5.9	138,000	0.3

use of a corrugated stainless steel diaphragm with the micromachined pressure sensor immersed in a silicone oil has also been utilized when exposure to corrosive fluids is required [31], [32].

A number of micromachined components need vacuum packaging for functionality or improved performance. Absolute vacuum reference pressure sensors [1], [2], [4], resonating micromachines [36]–[38], tunneling devices [39], and field emission displays all utilize vacuum sealing. This sealing can be done at the chip level using wafer-to-wafer bonding, or through a solder or weld hermetic seal performed under vacuum.

The package and assembly process can have a detrimental impact on microsystems. Since many micromachined sensors and actuators are fabricated from fragile semiconductor or ceramic, material breakage can be a packaging issue [3], [7], [40]. Many sensors are essentially strain gauges and so can pick up packaging-induced strain as well as the phenomena they are intended to detect. Often, packaging stress is not observed until the microsystem is exposed to temperature changes. Since automotive components see temperature changes of 125°C to over 400°C, this is a very critical source of stress. Differences in the thermal expansion coefficients of materials and in Young's modulus lead to these stresses. Table 2 shows a list of these important material properties (see modeling articles for data). Preventing severe thermal stress can best be accomplished early on in the packaging design stage using computer modeling [3], [40], [41]. Die-attach materials with low Young's modulus, as well as mounting sensor elements to glass pedestals using wafer bonding, have been employed to minimize package-induced stress.

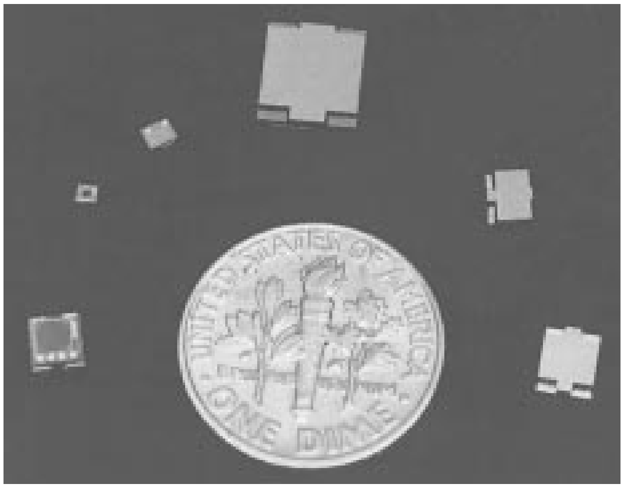

Fig. 4. Various sensors made using wafer bonding. From left to right: A silicon-to-glass bonded piezoresistive pressure sensor, a silicon-to-silicon bonded piezoresistive pressure sensor, a silicon-to-silicon bonded capacitive pressure sensor, two triple-stacked silicon accelerometers, and an angular rate sensor.

Packaging microsystems without breakage problems is just the first assembly step for many sensors. Lower levels of packaging stress can cause hysteresis and long-term output drift. Automotive customer specifications often call for less than 1–5% drift in output over time after prolonged operation or temperature cycling. Additional package-design improvements are required to meet such requirements.

Automotive customers expect component prices to be much lower than traditional medical, industrial, or aerospace microsystems. This can only be accomplished using inexpensive materials and designing the MEMS package to be easily tested and calibrated. This combination of reliable, stress-free packaging and system calibration often dominates the overall cost of the microsystem [11]. Micromachined devices will often be used to sense fluid pressure, flow rate, motion, or temperature. This requires custom test equipment. The variation in sensor output with temperature also requires calibration at different temperatures. These factors must be taken into account when designing a package in order to minimize the cost of the overall product.

X. COMMERCIAL AUTOMOTIVE MICROMACHINED DEVICES

Silicon micromachining has been used by the automotive industry since the mid-1970's [1]–[3], [5]. Fig. 4 shows a variety of pressure sensor cells. Silicon piezoresistive pressure sensors were the first automotive micromachined products. These devices have been manufactured using standard IC processing along with wet silicon etching and wafer bonding. These sensors were employed to monitor the intake air pressure and adjust the fuel-to-air ratio for improved fuel economy. This sensor technology was quickly applied to barometric and turbo boost monitoring in the automobile. Improvements in silicon etching technology have continued for these devices [25], [26]. Wet silicon etching initially was accomplished using timed etching and a P^+ etch-stop process. Electrochemical etching [25] is currently the process of choice for micromachined pressure sensors. Silicon-to-silicon bonding is replacing anodic and glass frit bonding for forming the reference vacuum. The two die on the left in Fig. 4 are piezoresistive pressure sensors. Die sizes have shrunk and wafer diameters have been increased to lower the cost of these sensors.

A more recently implemented automotive micromachined sensor that is being put on millions of cars is the fuel vapor pressure sensor. This sensor is used to detect fuel vapor leaks in the fuel tank in order to reduce raw fuel emissions into the environment. This device is similar to the 20-year-old absolute pressure sensor; however, it measures pressure down to the ±10 KPa range and is differential. The extreme pressure sensitivity of the fuel vapor sensor makes stresses induced by the package a very important issue.

Capacitive pressure sensors have also been developed [4], [42]–[45]. These devices have an advantage of lower power consumption over piezoresistive devices [4], and so have been applied to remote tire pressure sensors [46]. Additional areas of growth for future micromachined pressure sensors include monitoring suspension fluid, oil, fuel, air-conditioning fluid, transmission fluid, and steering fluid [4], [31], [32].

In the mid-1990's, micromachined accelerometers began to appear in cars for frontal impact detection associated with air-bag deployment [7]–[10]. Initially, the same type of bulk-micromachining processes were used to produce these device as had been used to fabricate pressure sensors. Currently, a mix of bulk-etched sensors and surface-micromachined devices are being used in the automobile for crash detection. Similar micromachined devices are now being applied to side-impact detection. High-g accelerometers for side-impact [7], [8] and low-g accelerometers for ride-control applications are areas of future growth for this type of micromachined motion sensor. The next motion sensor that will see high-volume application in the automotive industry is the angular rate sensor [36], [47], [48]. These micromachined sensor devices have been applied vehicle control systems in both the yaw and roll axis. Improved braking, safety, and navigational assist are areas in which these devices are being employed.

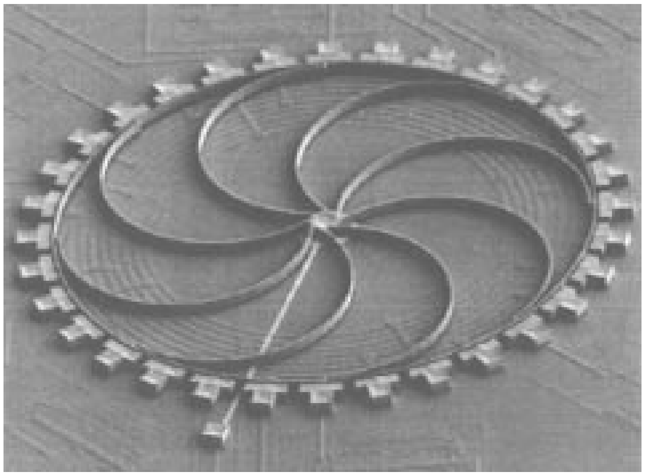

Fig. 5. A CMOS integrated, surface-micromachined angular rate sensor.

Fig. 5 shows a complementary metal–oxide–semiconductor (CMOS) integrated, electroformed device, used for angular rate sensing. Shown is a thin ring structure, 1 mm in diameter, supported by eight semicircular springs that join together at the center supporting post. The ring and spring structure is surrounded by 32 electrodes equally spaced around the outside of the ring. Under this electroformed ring, spring, and electrode structure, the features of the on-chip silicon circuitry can be seen. The electrode-ring gaps are used to drive the ring electrostatically into resonance and to monitor the vibration pattern capacitively in the ring.

The sensor device measures rotation rate by monitoring the position of node lines in a vibrating ring. To sense rotation rate, the ring is electrostatically forced into an elliptically shaped resonant mode, and the position of the node lines is capacitively monitored. When the sensor chip is rotated about the axis of the ring, the node lines lag behind the chip rotation due to the Coriolis force. The control and signal conditioning circuitry monitors this lag and develops a corrective voltage to hold the node lines fixed with respect to the chip reference using a force-rebalance measurement scheme. This feedback voltage is directly proportional to the angular rate. Due to the symmetric resonant mode pattern, the sensor rejects any linear motion as a possible interference [36]–[38].

An increasing number of micromachined devices that are not sensors are finding their way into the automobile. Fuel-injector nozzles [49]–[52], valves [53]–[57], microphones [58], microswitches or microrelays [59], fiber-optic links [60], [61], radio-frequency (RF) elements [62], and displays [63]–[65] using micromirrors or micromachined emitter tips are examples of nonsensing micromachines that have been or will be applied to the automobile. Like sensors, packaging or the merger of the silicon micromachine with the vehicle is critical.

Silicon poppet valves have been used in the fuel-flow system of an automobile [53]. Due to silicon's brittle nature and expansion coefficient difference with most steel, this merger can present problems. Controlling fluid flow also requires sensing it. Micromachined flow sensors have also been developed and could see use in sensing various automotive fluid-flow rates and directions [7], [66]. Microsensors capable of detecting different gases have also been developed [67]–[69] and could find themselves in vehicles.

Relays are used for distribution of current loads. The most common type of relay is mechanical in nature but is electromagnetically activated. These relays are reliable and inexpensive and can carry high current. The drawback to the present devices is their size and requirement for continuous current to maintain contact. Solid-state transistors are the second most popular relay. These devices can be inexpensive for low-current applications, but heat-sink requirements at high current loads can drive up the cost of these semiconductor relays. Recently, micromachined relays have been fabricated by using LIGA or LIGA-like electroforming technologies [59]. Microrelays are actuated either electrostatically or electromagnetically. The electroformed relays have the advantage of transistor relays: small size, batch fabrication, and hence lower costs. They also have the potential advantages of mechanical relays: lower contact resistance and no need for a heat sink. Up to now, the current-carrying capability of micromachined relays was limited to the milliampere range. Additional research is needed to increase the current-carrying capability of these micromachines.

There are a number of emerging MEMS technologies that will eventually find a place in the passenger compartment of the automobile. Tomorrow's vehicle will be filled with various communications devices [70], which will be linked to the outside world via satellites and microwave towers. Cellular phones, General Motors' OnStar program, and Internet and fax access are examples of current vehicular communications devices. Micromachined RF devices have been proposed as a way of shrinking and lowering the cost of future communications devices [62]. As in the case of other MEMS technologies, the military and aerospace industry will lead in the adoption of these micromachined devices.

Electromagnetic interference is another area that can affect communications both inside and outside of a vehicle. Fiber-optic cables are one method of reducing the susceptibility of automotive systems to electromagnetic interference. Micromachined optical switches and couplers [60], [61] may be a way that MEMS may contribute to solving this automotive problem. Display technology is another area of development in the automotive industry. Heads-up display (HUD) technology has been borrowed from the aerospace industry and applied to vehicles [71]. There are many micromachining methods that have been used to form displays. These include micromirrors [63], deformable grates [64], and field emission arrays [65]. High-intensity projection systems for HUD and smaller dashboard displays lend themselves to micromachined displays.

XI. FUTURE TRENDS

Bus communication is becoming a necessity in modern vehicles. Systems such as CLASS 2, controller area networks, and local-area networks are being employed on vehicles worldwide. By using a common bus architecture, sensor and wire duplication is avoided and wiring becomes easier as the harness size goes down. Just reducing the number of cable connectors, via a bus, improves system reliability, minimizes repair problems, and makes fault detection simpler. Transducers, which are linked together with microprocessors through a common bus, are often called smart sensors and actuators [72]–[74].

Smart sensors are currently made by using multiple chips. However, since many processes used to fabricate micromachines are taken from the integrated circuit arena, it is only natural that micromachines and circuitry should gradually merge together. Accelerometers were the first area in which this was begun in high volumes [10]. Angular rate sensors, like that in Fig. 5, appear to be the next device that will employ this combination [36]–[38]. Smart sensors do more than just send a signal; they have algorithms that interpret data, communicate, and/or self-calibrate over time. Integrating bus interface circuitry is a future development that will start at the module level and spread to the chip.

XII. SUMMARY

Automotive sensors and actuators represent a major market for the MEMS technology. However, there are many development issues that must be brought into balance for a sensor or actuator technology to be commercially viable for automotive applications. This paper has examined the sensor and actuator development issues unique to the automotive industry. The future is bright for even greater penetration of these devices in automotive products.

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David S. Eddy received the B.S. and M.S. degrees in electrical engineering from the University of Michigan, Ann Arbor, in 1959 and 1960, respectively.

In 1960, he joined the Staff of General Motors Research Laboratories, where he has worked in a number of technical areas related to solid-state devices and sensors for automotive applications. For the past 18 years, he has led a group of researchers focusing on the development of new sensor devices that can be manufactured in high volume and for low cost as the enablers for advanced automotive systems.

Douglas R. Sparks received the Ph.D. degree from Purdue University, West Lafayette, IN.

He has been with Delphi Delco Electronics Systems for 14 years, working in the areas of sensor and semiconductor device and process development. Prior to that, he was with Cincinnati Milacron's Semiconductor Material Division and the Turner Electroceramics Laboratory at Purdue University. He has published numerous technical articles and has received ten patents.