International Conference on Recent Innovations in Engineering and Management
Dhananjay Mahadik Group of Institutions (BIMAT) Kolhapur, Maharashtra (ICRIEM-16)
23rd March 2016, www.conferenceworld.in ISBN: 978-81-932074-5-1

A REVIEW ON MEMS APPLICATION IN AUTOMOTIVE SENSORS

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ABSTRACT

Sensors 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, form the backbone of present and future automotive systems. Unit volumes for sensors in the automotive industry are measured in millions per year and at a unit cost of a few Euros. The design of sensors has increasingly made use of microelectromechanical systems (MEMS) technology. This technology is well suited to producing a class of micro-machined sensors that combines signal processing and communications on a single silicon chip or contained within the same package. This paper contains a discussion on the issues in producing MEMS sensor from the concept selection stage to the manufacturing platform. Examples of commercial and emerging automotive sensors 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, automotive systems, microelectromechanical systems, micromachines, pressure sensors.**

I. INTRODUCTION

Sensors are components of automotive electronic control systems. Hence, the types of sensors 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 manufactured in high-volume operations. The types of automotive systems currently found on most modern vehicles are those that control engine, power train, suspension, and braking, along with utility systems that

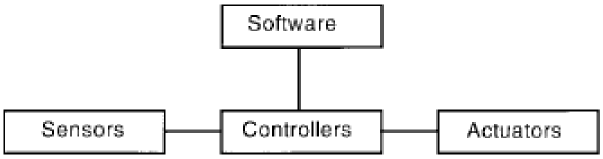

Fig. 1.1 Functional partitioning of automotive systems.

Control the vehicle body functions, and information systems for communication within the vehicle as well as externally.

Since about 1985, 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 Chassis-control power train, 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. 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:

- An overall principle of operation;
- Device modeling;
- Materials technology system;
- Manufacturing system for high volume production
- e). Packaging and interconnection system;

Because of the multifaceted nature of sensor and actuator development, these aspects must be addressed globally in the 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.

III. IMPORTANT POINTS OBSERVED

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

- **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.

- **Device Modeling**

Analytical and computer-aided design (CAD/CAMD) 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.

- **Materials Technology System**

With MEMS technology, compatibility with the materials and operations in a production silicon integrated circuit (IC) the 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.

- **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 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.

- **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 (no more than three) of wires connecting the sensor to the system is usually a requirement in order to keep the sensor cost low.

IV. 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 110 direction, are known to have the highest gauge factor of common piezoresistive material. 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 -space energy surfaces. Since CMOS and bipolar integrated circuits are fabricated from (100) silicon wafers, this transduction principle was adopted by the first micro-systems. Piezoresistive devices have been and still are currently employed in millions of micro-machined pressure sensors, accelerometers, and flow sensors [1-8]. 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 micro-machined 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 forcers balance measurement techniques can be used effectively with capacitive sensors.

4.1 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 micro-system's environment may require predictions of fluid flow or the effect of thermal expansion coefficient differences between materials used to house the micro-machine. 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 micro-machined 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]. In case of other micro-devices, parameters such as 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. Once a general micro-machine structural model is complete, fabrication simulation can be undertaken. With silicon-based micro-systems, 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 micro-machine 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 micro-device. Just as IC simulation programs have been linked together, MEMS simulation software that joins mechanical process and electrical design has also been developed [19]–[21]. Extensive experimental work is required to optimize the accuracy of any model with results obtained in the factory. Non calibrated modeling is useful for first-order development; however, confidence in any simulation package is only obtained with verification.

4.2 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 micro-machine 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

Temperature	-45^0c to 85^0c driver interior. 200^0c -600^0c exhaust and combustion chamber
Mechanical Shock	3000g during assembly(drop test)
Mechanical Vibration	15g, 100Hz- 2KHz
Electromagnetic Impulses	100-200 Volts per meter
Exposure to	Humidity and salt spray and Freon.

Table 1 The Automotive Environment

From the transistor collector process and any N+ substrate tie came from the bipolar emitter process. In some cases, even the P+ stop was derived from top-side/bottom side junction-isolation P buried-layer process modules. Metal and passivity layers were also borrowed from existing bipolar process flows. Twenty three years ago, process modeling was rarely employed, and processing experiments were used to adjust these existing bipolar IC processes into a manufactured micromachining fabrication sequence. Most original work was required in the areas of silicon etching [22]–[23],

In a similar manner, most piezoresistive accelerometers were derived from already existing micro-machined pressure sensor processes. Silicon doping, photolithography, oxidation, 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. Other capacitive accelerometers borrowed from conventional CMOS or BICMOS processing in the same way. Radically new micro-machined 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 micro-devices.

4.3 Selection of Mems Components

The selection of automotive MEMS components must begin with a consideration of the environment to which the micro-system 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. 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.

Mechanical package design is the next level of protection for a micro-system. 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. The use of a corrugated stainless steel diaphragm with the micro-machined pressure sensor immersed in a silicone oil has also been utilized when exposure to corrosive fluids is required [16-17].

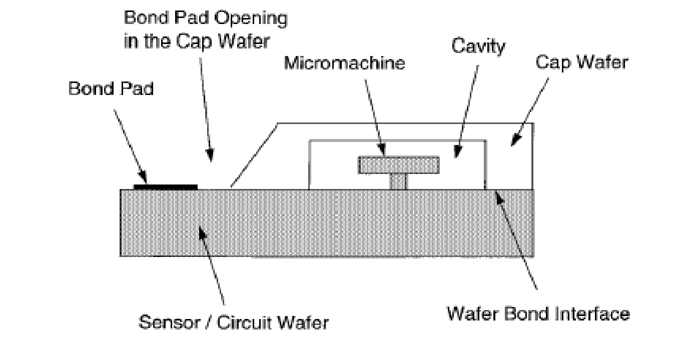

Fig. 3. A cross-sectional view of a chip-level packaged micro-machined sensor.

Material	CTE(ppm/K)	Young's Modulus(Mpa)	Poison's Ratio
Silicon	1.8-3.2	162000	0.28
Silicone RTV	800	6.9	0.4
Pb37-Sn63 solder	28	23000	0.4
7740 Glass	3.3	62784	0.2
Alumina	5.1-7.5	276000	0.23
FR-4	15	18200	0.25
Kovar	5.9	138000	0.3

Table 2 MEMS Material Properties

A number of micro-machined components need vacuum packaging for functionality or improved performance. Absolute vacuum reference pressure sensors [1-4], resonating micro-machines [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 micro-systems. Since many micro-machined sensors and actuators are fabricated from fragile semiconductor or ceramic, material breakage can be a packaging issue [3], [7]. 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 micro-system 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 preventing severe thermal stress can best be accomplished early on in the packaging design stage using computer modeling [3]. Automotive customers expect component prices to be much lower than traditional medical, industrial, or aerospace micro-systems. 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 micro-system [11]. Micro-machined 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.

V. AUTOMOTIVE MICRO-MACHINED DEVICES

Silicon micromachining has been used by the automotive industry since the mid-1970's [1-5].Silicon piezoresistive pressure sensors were the first automotive micro-machined 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], [23]. Wet silicon etching initially was accomplished using timed etching and a P etch-stop process. Electrochemical etching is currently the process of choice for micro-machined pressure sensors. Silicon-to-silicon bonding is replacing anodic and glass frit bonding for forming the reference vacuum. A more recently implemented automotive micro-machined 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-yearold 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], [24]–[25]. These devices have an advantage of lower power consumption over piezoresistive devices, and so have been applied to remote tire pressure sensors. Additional areas of growth for future micro-machined pressure sensors include monitoring suspension fluid, oil, fuel, air-conditioning fluid, transmission fluid, and steering fluid [16-17].

The sensor device measures rotation rate by monitoring the position of node lines in a vibrating ring. To sense rotation rate, the ring is electro statically forced into an elliptically shaped resonant mode, and the position of the node lines is capacitive 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 micro-machined devices that are not sensors are finding their way into the automobile. Fuel injector nozzles, valves, microphones, micro switches or micro-relays, fiber-optic links radio-frequency (RF) elements, and displays using micro-mirrors or micro-machined emitter tips are examples of non sensing micromachines that have been or will be applied to the automobile. Like sensors, packaging or the merger of the silicon micro-machine with the vehicle is critical. Silicon poppet valves have been used in the fuel-flow system of an automobile. 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. Micro-machined flow sensors have also been developed and could see use in sensing various automotive fluid-flow rates and directions. Micro-sensors capable of detecting different gases have also been developed [28]–[30] and could find themselves in vehicles.

There is a number of emerging MEMS technologies that will eventually find a place in the passenger compartment of the automobile. Today's vehicle will be filled with various communications devices, which will be linked to the outside world via satellites and microwave towers. Cellular phones, General Motors' On Star program, and Internet and fax access are examples of current vehicular communications devices. Micro-machined RF devices have been proposed as a way of shrinking and lowering the cost of future communications devices. As in the case of other MEMS technologies, the military and aerospace industry will lead in the adoption of these micro-machined 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. Micro-machined optical switches and couplers 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. Deformable grates [27] and field emission arrays. High-intensity projection systems for HUD and smaller dashboard displays lend themselves to micro-machined displays.

VI. CONCLUSIONS

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 reviewed 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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