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A Monolithic Integrated Solution for MAP Applications

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ABSTRACT

A monolithic sensing solution for manifold absolute pressure (MAP) is presented. This work includes examination of design, fabrication, temperature compensation, packaging and electromagnetic compatibility (EMC) testing of the fully integrated monolithic sensor. The circuit uses integrated bipolar electronics and conventional IC processing. The amplification circuit consists of three op–amps, seven laser trimmable resistors, and other active and passive components. Also discussed is a summary of an automotive application MAP sensor general specification, test methods, assembly, packaging, reliability and media testing for a single chip solution.

INTRODUCTION

Ever increasing requirements for better fuel economy, safety, and comfort in automobiles has put demand on the sensor industries to develop a high quality, more reliable, and lower cost sensor for use in high volume manufacturing. The stringent requirement of the Corporate Average Fuel Economy (CAFE) regulations makes it necessary for sensors to be incorporated into automotive electronics. There are several sensors used in today's automobile to fulfill the above needs [1,2,3], and among them are many silicon based sensors. One of these is a MAP application. The first silicon based MAP sensor was incorporated in automobiles in the 1980's [4].

Two of the technologies developed in early 80's for MAP application were capacitive and piezoresistive (PRT) pressure sensors. The capacitive pressure sensor known as SCAP (silicon capacitive absolute pressure sensor) was incorporated in Ford Motor Company vehicles, and the piezoresistive sensor was incorporated by a number of other automobile manufacturers. However, these technologies utilized sensing elements with no signal conditioning. In some cases the sensor included a resistor network for temperature compensation but did not incorporate signal conditioning on the same chip.

An integrated sensor offers a cost effective solution. A small die size offers an opportunity to reduce the package size, especially important where expensive materials are used for housing sensors [5]. In addition, an integrated sensor is less susceptible to outside interference where wire interconnects the transducer and control circuitry and introduces the coupling of EMI into the system. An integrated sensor also improves yield and reliability by having fewer connections where failures can occur [6]. The connections are usually exposed to harsh media environments and are more susceptible to corrosion and other potential failures [6].

To date, most silicon–based automotive pressure sensors do not have integrated circuitry on the same chip. The availability of reliable low cost integrated technology coupled with silicon micromachining has increased the number of potential applications for fully integrated pressure sensors. In recent years, development of new technologies for better media and environmental protection, along with better sensor fabrication techniques has resulted in a robust piezoresistive pressure sensors.

MAIN SECTION

PRINCIPLES OF OPERATION — MAP sensors measure the vacuum in the intake manifold. When the engine goes through an intake cycle, a given cylinder receives the fuel–air charge from the intake manifold. The pressure measurement from the intake manifold is provided to the engine control unit (ECU), which then calculates the MAF (mass air flow) rate from the pressure measurement using the following equation [7]

$$\text{Mass Air Flow} = \frac{N \bullet MAP \bullet \text{displacement} \bullet RPM}{T_{Charge}}$$

where N is an empirically determined factor, usually about 0.6, MAP is the intake manifold absolute pressure, displacement is the volume of the cylinders multiplied by the number of cylinders, RPM is the engine rotation in revolutions per minute, and T_{charge} is the temperature of the air/fuel charge. The data is used to adjust the vehicle's injector pulse width, thereby insuring optimum engine stoichiometry and preventing a lean burn.

The MAP sensor general specification and testing requirements varies for the different automakers. The specifications usually depend on their algorithm, technology, and system requirements. A typical MAP sensor specification and testing requirements is shown in Table 1. The typical pressure range for the MAP sensor is 105 kPa full scale. However, in the case of turbo charged engines, the pressure range is typically 250 kPaA full scale.

REV 1

Table 1. General MAP Requirements

Transfer Function	V_{out} = Vs (P • K_1 – K_2) ± Error, K_1 & K_2 are constants
Low pressure requirement (kPaA)	15
High pressure requirement (kPaA)	250
Ratiometricity	1% ± 0.5% for 1% Vs change
Power suppy (V)	Typically 5.0 ± regulated
Response time (ms)	≤15
Sink (mA)	.08 to 1
Source (mA)	.20 to 5
Thermal cycle — unpowered	200 to 700 cycles, –40/125°C, 60 min/cycle
Pressure/Temp Cycle	200 to 3000 cycles, –40/125°C, 0.5 to 1.5 hr/cycle
Hot Storage (Powered)	100 to 1000 hrs, 125°C
Hot Storage (Unpowered)	500 to 1000 hrs, 125°C
Cold Storage (Unpowered)	96 to 1000 hrs, –40°C
Humidity	96 to 1000 hrs, 60 to 85°C, 85 to 90% RH, with or without bias
Drop	1 to 5 drops of 1 meter
Mechanical Shock	5 to 100 g pulses of 10 msec
EMC/EMI (susceptibility)	50 to 200 V/M, 1 to 1000 MHz

MONOLITHIC DESIGN — Figure 1 shows the top view of an integrated pressure sensor. The monolithic sensor contains op–amps, and passive components including SiCr resistors for laser trimming. This is an analog device which uses bipolar integrated circuit technology. The single–chip MAP sensor uses a single series temperature compensation of span resistor which provides a varying common mode voltage for use in temperature compensation of offset trimming. A total of three op amps are used in the sensor design. The first two form an instrumentation amplifier to isolate the transducer output from the resistor network. The third is the output buffer with level shifting divider R_8 and R_9, and zero pressure offset pedestal set by R_{10} and R_{11} (see Figure 2). TC of offset is corrected by shifting the negative side of the transducer differential output with temperature. Zero pressure offset is trimmed at the divider (R_8 and R_9) and pull–up resistor to Vcc (R_7), which allows minor adjustments independent of gain.

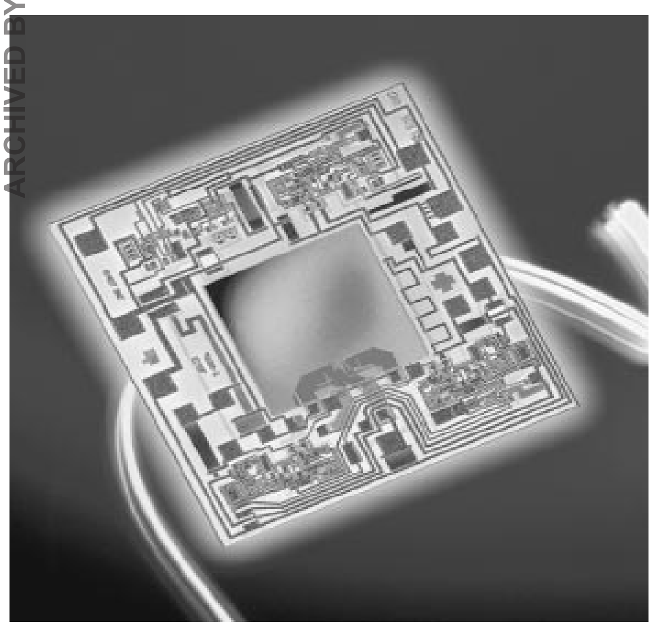

Figure 1. Top View of an Integrated Pressure Sensor

The sensing transducer design is a single piezoresistive element. It consists of a diaphragm and a piezoresistive element located near the edge of diaphragm at a 45% angle [8]. The diaphragm size is about 1000 microns and thickness is about 20 microns. The die size is approximately 3 mm^2..

SOURCE/SINK — The first single–chip MAP sensor was designed to interface directly with the A/D inputs of a microprocessor. The output signal encompasses the upper rail voltage minus a saturation voltage for the PNP output driver and ground plus a similar voltage to allow for a reasonable output leakage current across the load resistor for maximum resolution by the microprocessor A/D. The sensor output is ratiometric when µP Vref–hi supplies the positive supply voltage and Vref–lo is ground. The high input impedance of the microprocessor combined with the source only output of the sensor requires a filter of 51kΩ in parallel with 50pf to insure cancellation of high frequency noise.

Since the first single–chip MAP sensor was designed to drive only the high impedance input of a microprocessor, additional current requirements (for EMI suppression, corrosion prevention, or implementation of a logic function) require additional source current / sink current drive capability. This is easily accomplished by adding an op amp buffer at the sensor output. The change in current drain is minimal. Accuracy is not affected since the only error is the op amp input offset voltage of only a few millivolts over temperature. Any load, accuracy, and current drain can be accommodated by the choice of a suitable op amp for the buffer.

LASER TRIMMING — All system level resistors are SiCr which has a thermal coefficient of resistance (TCR) of near zero. The TCR is important for the series span compensation resistor (Rs) since span decreases with temperature (see Figure 2). Since the transducer input resistance increases with temperature, the series resistor will cause the voltage across the transducer to increase. This increase in voltage across the transducer counteracts a loss in sensitivity. The room temperature voltage must be set to a value which will cause the excitation voltage (Vex) to increase at a proper rate.

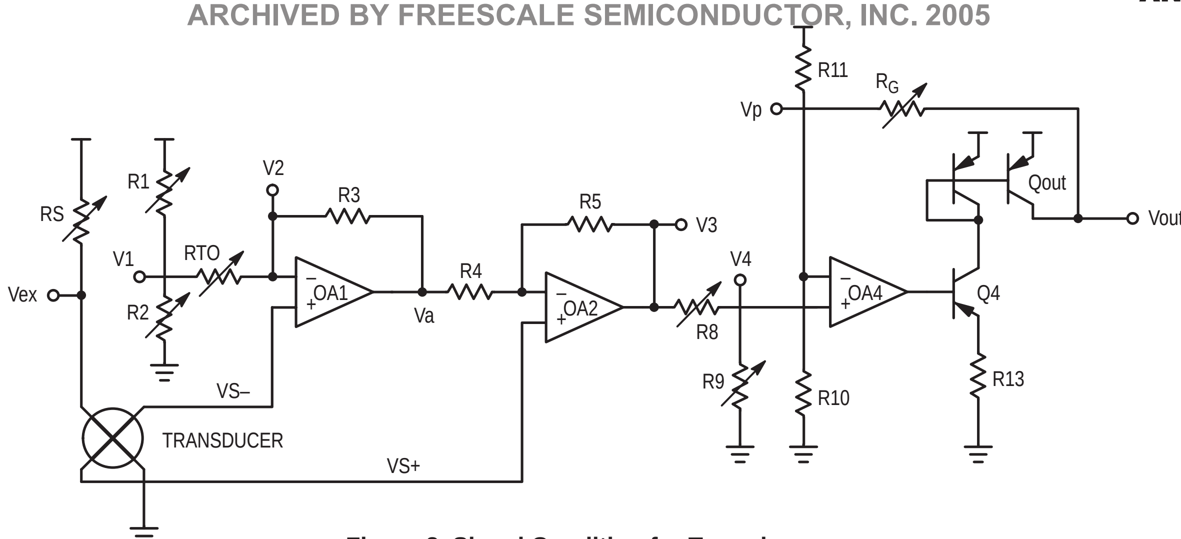

Figure 2. Signal Condition for Transducer

Next, the pressure to the device is set to the minimum level, R1 or R2 is trimmed to set V1=V2, and the offset is adjusted to 0.2V by adjusting the divider R8 or R9. The divider value is set to approximately cancel the transducer common mode voltage. With pressure applied, Rg is trimmed to set the desired sensitivity. The input network of OA4 allows gain to be adjusted without changing the previously trimmed offset.

The device must then be heated to trim TC of offset. At elevated temperature, V2 is now above V1, and current will flow into RTO. RTO is trimmed at the minimum pressure and elevated temperature to achieve the same offset voltage as set at room temperature, 0.2 V in this case.

PROCESS — The MAP sensor consists of bipolar integrated circuit and a micromachined sensing element on a single monolithic chip. Both bipolar processing and sensor fabrication are well established technologies. However, marrying these technologies presents some challenges, since the sensor fabrication requires non–conventional IC processing such as a deep etching of the silicon to form a thin diaphragm (see Figure 3).

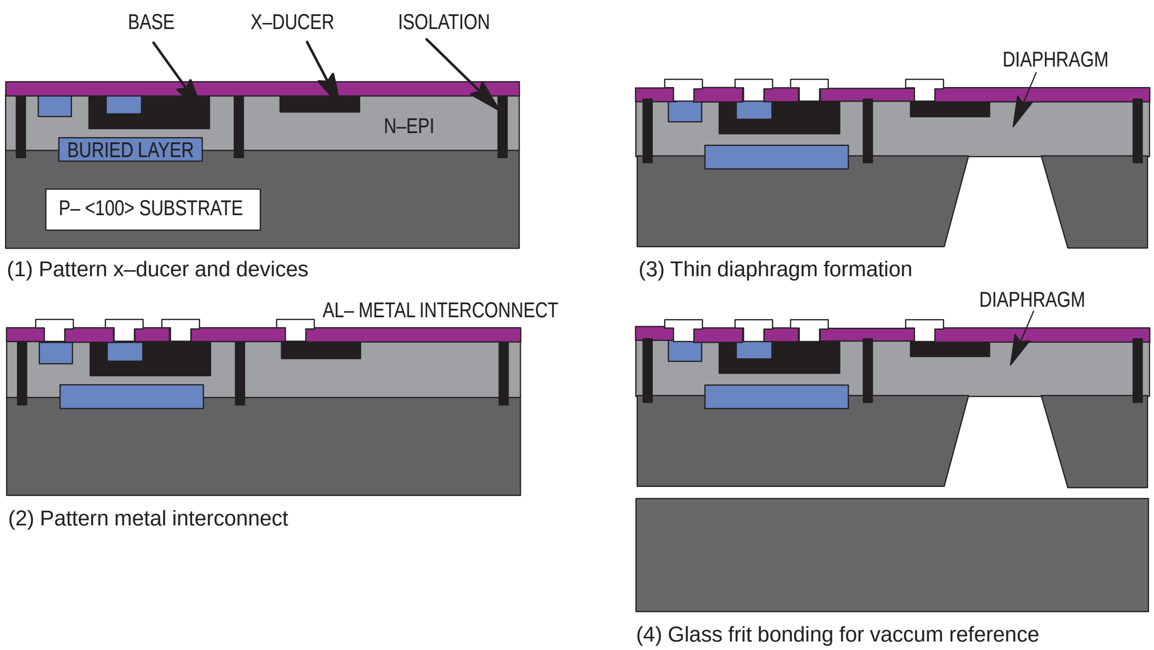

Figure 3. Process Sequence for Generic Integrated Absolute Pressure Sensor

A typical sequence of fabrication steps illustrating the technique is shown in Figure 3 for a generic integrated piezoresistive sensor (IPS). The X–ducer™ and bipolar devices were fabricated using conventional IC diffusion processing. Following the diffusion, SiCr thin films and interconnect metalization is deposited and patterned. Aluminum is used as the interconnect metalization. Once the device fabrication is completed, a deep anisotropic cavity is etched into the silicon from the back side of the wafer to form the diaphragm. The active wafer is then frit bonded to a constraint in an evacuated chamber, forming an absolute reference cavity below the diaphragm.

EMC PERFORMANCE — Electromagnetic compatibility is a major issue for automotive applications. The specifications and bench test set up for EMI testing is not standardized across the industry. The test method discussed here is most severe and adequate enough to meet most of the requirements, i.e., device capable of lower susceptibility or greater resistance to the present electromagnetic (EM) signals.

Figure 4 describes the test setup. More detail of the setup, testing conditions and test results are described elsewhere [9]. The requirement for testing integrated sensor involves a 200 V/m radiated immunity test from 10 kHz to 1 Ghz. The test can be extended to higher frequency to evaluate influence of the 1–18 GHz signals.

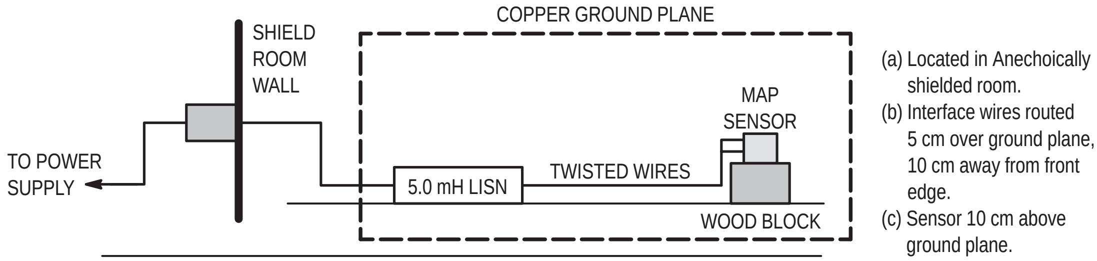

Figure 4. EMC Test Setup

Tested pressure sensors met the requirement and did not exceed the AC ripple or DC offset susceptibility criteria over the 200 MHz to 1GHz frequency range. Measurements were repeated several times over time periods as long as several days with the same test setups, and results show very similar values.

PACKAGING — One of the great challenges in semiconductor sensor manufacturing is the packaging. Unlike IC packaging, the pressure sensor can be directly exposed to harsh media. Thus, it requires more than the concepts that evolved out of conventional IC packaging technology. The suitable material and mounting techniques to provide include: (a) mechanical support, (b) electrical interface, (c) environmental protection, and (d) media interface (see Figure 5). Typical requirements for sensor packaging are discussed below.

– Media Compatibility
  – Fluro Silicone Gel
  – RTV Die Bond
  – Exposed Die

– External Package Stresses
  – Porting Stresses
  – Stresses From Lead Form
  – Direct Stresses on Package

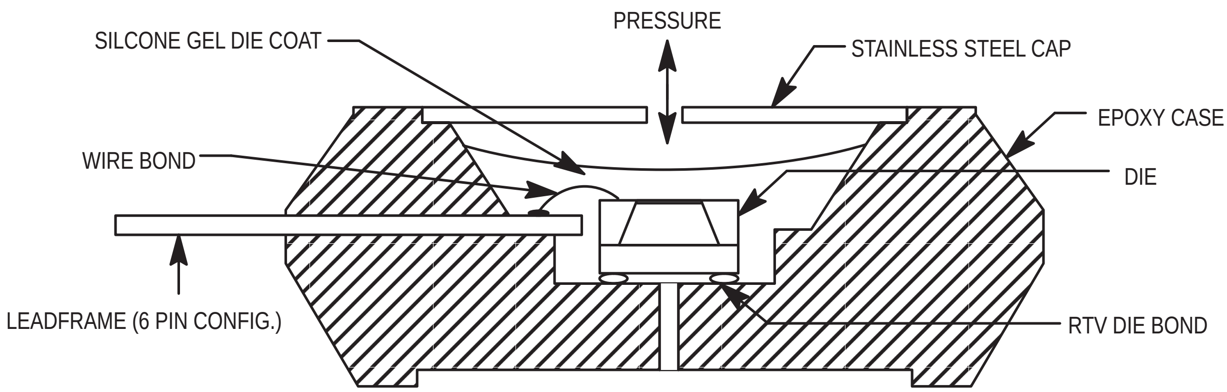

Figure 5. Basic Chip Carrier Package

The number of leads in sensor packaging varies according to the product and its application. The IPS package described here is designed with eight pins. The actual number of pins used by the customer is only three. The additional pins are used for laser trimming and are not connected in the application. The leads are designed with width of 1.27 mm (50 mil) and 2.54 mm (100 mil) spacing. For Surface Mount and other packages (Piston fit), the leads are formed to create a gull–wing shape or can be formed for a through hole solder joint. The piston fit package is designed to accept an O–ring to create either a radial pressure seal or a surface seal using a soft material such as silicone. Several versions of the piston fit package are shown in Figure 6. The size, spacing and the shape of the leads follow a standard practice, thus no special requirements for pad layout or via hole is required during PWB layout. The solder bond pad sizes and solder paste application will be same as other semiconductor components.

Conventional semiconductor components are typically shipped with leads that are solder dipped or tin plated after overmolding. This is not a major issue since the packages are not open to the atmosphere. For pressure sensor packages, there is always an opening for pressure interface. The lead configuration makes it difficult to perform solder dipping or tin plating. Without such a treatment, the underlying Ni layer may not pass the solderability requirement. An acceptable solution to the solderability issue is to provide a flash of Au on the solderable portion of the leads, which would protect the underlying Ni. In surface mount assembly with Sn–Pb solder, the presence of Au is known to form Au–Sn intermetallic. An

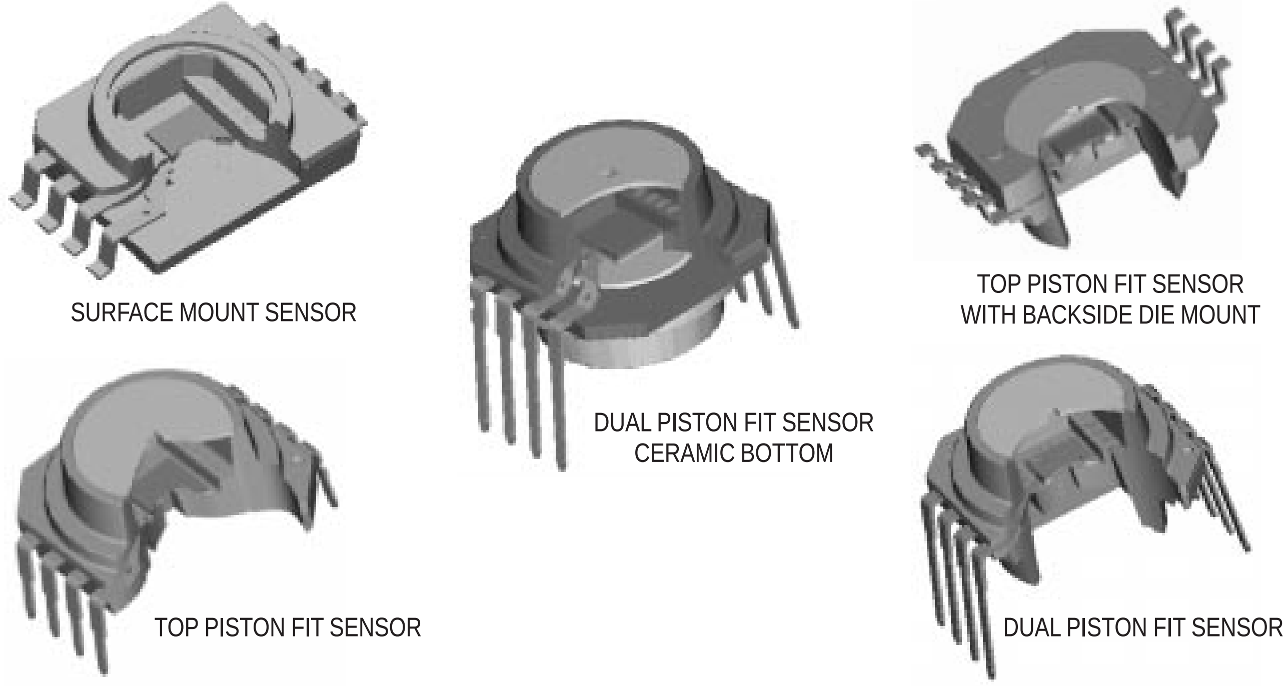

Figure 6. Surface mount and piston fit packages. The top and dual piston fit packages are designed to accept an o–ring for the pressure interconnect.

excessive amount of Au is likely to cause embrittlement of the solder joint, which will result in lower fatigue life. A solution adopted by Motorola and many other sensor manufacturers is to use a flash of Au on the lead frame, which would maintain solderability of the lead at the same time introduce fairly insignificant amount of Au in the Pb–Sn solder. In a typical solder joint, this amount of Au will result in approximately 1% of Au in the solder; which is significantly less than commonly acceptable 5% Au in the solder joint.

For a MAP application, the sensor needs to sense the manifold vacuum pressure. Therefore, it needs to have either a port which will be connected to vacuum hose, or it will be mounted in another housing with a port. These housings are either directly mounted to the manifold or externally mounted under the hood. The direct mount configuration is shown in Figure 7. The advantage of this technique is that the method does not require any hose to connect to the sensor thereby reducing the system cost. The draw back is that the sensor housing experiences significantly higher temperatures. This higher temperature may result in different housing materials and could influence the electrical specification.

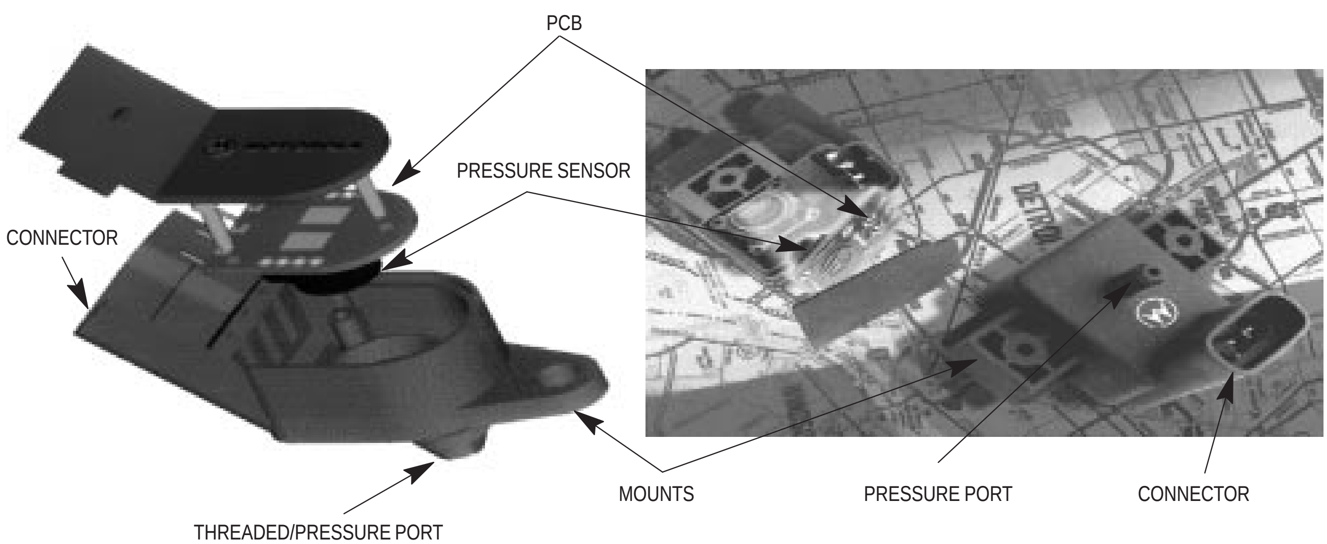

Figure 7. Conceptual Housing Options for User Implementation

The MAP sensor can also mounted direct on the ECU, eliminating the need for a wire harness and external connector. This will result in a lower system cost and less source and sink current requirements since the external connector is eliminated. For this configuration, the pressure hose needs to be extended from the manifold.

RELIABILITY AND MEDIA TESTING — To ensure accurate testing, knowledge of the application, lifetime requirements, and what constitutes a failure is crucial. A physics–of–failure approach can significantly reduce the development cycle time and produce a higher quality product [10]. The focus of the physics–of–failure approach includes an understanding of the application, lifetime expectation, failure mechanism(s), and lifetime models. The requirement for a typical MAP or BAP pressure sensor application involves testing to temperature extremes, thermal cycle, humidity, media exposure, vibration, shock, cyclic pressure, and overpressure testing [11]. Through reliability testing and knowledge of the environment, potential failure mechanisms are uncovered. A complete listing of potential failure mechanisms that may affect a pressure sensor device has been presented elsewhere [12].

The MAP application requires the sensor to survive in a fuel or aqueous solution. The fuel exposure typically is performed at elevated temperature to a wide variety of fuel types. A test matrix of several fuels based on ASTM guidelines that includes various additives such as methanol, water, or acids and a test procedure have been discussed elsewhere [13]. Acid testing either performed independent to the fuel or following exposure has proven to be an affective test scheme for product development. The nitric and sulfuric acid tests are a concern due to NO_x + water = HNO_3 and SO_x + water = H_2SO_4. A proposed test scheme for product development involves a variety of material types and environments. Not all materials from the same family will respond the same to the testing. Actual media test results will be published elsewhere.

A key aspect to reliability and media testing involves the determination of what constitutes a failure. The definition of an electrical failure can range from catastrophic, to exceeding a predetermined limit, to just a small shift. The traditional pre to post electrical characterization before and after the test interval can be enhanced by *in situ* monitoring. In situ monitoring may expose a problem with the sensor device during testing that may go undetected once the media or another environmental factor is removed. For example, swelling of polymeric materials when exposed to certain media or environment, may result in shift in the device output. Such a failure mechanism can only be detected by insitu monitoring. Response variables during environmental testing can include: electrical, visual, analytical, or a physical characteristic such as swelling or weight change. A typical definition of failure for the MAP and BAP application is to both be within the error budget after the exposure. In addition, the output voltage shift from the initial value needs to be within a predetermined value.

X–ducer is a trademark of Motorola, Inc.

CONCLUSION

A monolithic integrated pressure sensor has been developed for MAP applications. The integrated pressure sensor is small in size and provides better performance than its predecessors. The sensor can be directly mounted on the ECU PWB or underhood. It shows great resistance to harsh media thereby making it well suited for automotive applications. Additionally, the monolithic integrated pressure sensor shows very good immunity to surrounding electromagnetic fields since the need for an interconnect is eliminated.

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