Features
Advanced automotive sensors

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Abstract

Reports on a one-day Institute of Physics seminar on new developments in automotive sensors for hostile environments. Provides details of the nine papers presented.

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Emerald

A one-day meeting was held by the Instrument Science and Technology (ISAT) group of the Institute of Physics on November 6, 2001, entitled "*New generation automotive sensors: The challenge of hostile environments*". The nine presentations covered topics ranging from the development of sensing devices and underlying technologies to sensor testing, protection and packaging.

Very much in keeping with the main theme of the event were two papers devoted to packaging for harsh environments. As the trend in the automotive industry is for sensors and electronics to be integrated on the same substrate, or at least incorporated into the same package, electronic components, substrates and connectors etc., rather than just the sensors, featured strongly.

A paper from TWI Ltd., "Packaging for harsh environments", focused largely on thermal effects but also highlighted some of the other potentially detrimental factors that automotive sensors need to withstand, e.g. moisture, salt, fuel, brake fluid, strong detergents (in car washes), exhaust gases and all manner of mechanical stresses. Packaging plays a key and often overlooked role in the design of an automotive sensor and whilst often just viewed as a containment device, the package often has to satisfy a host of different functions, e.g. device location, device protection, internal inter-connections, external interconnections, mechanical connection to the sensor, heat sinking/cooling and EMI shielding. As noted by the speaker "*Packaging materials/design/choices influence performance, reliability, size, weight and cost*". Many examples were given of the thermal tolerances of the key components used in packaged sensors and Table I shows that, for operating temperatures of up to about 200°C or perhaps 250°C, silicon sensors and conventional electronics are generally adequate but for use above this point, non-silicon electronics and other, as yet immature, technologies must be developed.

In addition to the sensors and electronics, other components and materials that need to be considered closely include substrates, adhesives, solders, interconnect materials, bonding wires and the outer package itself, and as well as operating temperature limits, several other factors need to be taken into account. These include thermal coefficients of expansion, deformation, thermal conductivity, electrical conductivity, chemical

Table I Thermal limits and technological maturity of electronic and sensor

Material	Technological maturity	Maximum operating temperature (°C)
Silicon	Very high	200–250
Silicon-on-insulator	Medium	250–300
Gallium arsenide	High (telecoms)	350–400
Gallium nitride	Very low	500+
Silicon carbide	Low	600–750+
Diamond	Very low	1000–1100

resistance, ageing and creep effects and most importantly, compatibility with cost-effective production methods.

"Fit for purpose packaging methods for next generation automotive sensors" was the title of a presentation by a speaker from Micro Circuit Engineering. This focused very much on some of the specific packaging requirements of advanced, micromachined sensors such as silicon gyroscopes and accelerometers. It is evident that, whilst enormous effort is devoted to sensor development, the final package is frequently overlooked, despite the often exceptional packaging demands of some microsensors. In the case of resonating sensors (e.g. silicon gyroscopes), or others with exceptionally small moving parts (e.g. accelerometers), the presence or subsequent ingress of gases, moisture or other contaminants will degrade performance.

Some of the key requirements for an automotive gyroscope include:

- Operation in a vacuum (pressure $< 10\,\mathrm{mbar}$);
- Lifetime of > 10 years;
- Low unit cost;
- High sensitivity and stability;
- Protection from harsh operating environment.

The vacuum operation, in particular, poses significant technical problems: the package's leak rate over the sensor's life must be minimised; materials within the package (e.g. adhesives) must not outgass significantly; and there is the need to resolve the conflict between minimising the volume requiring the vacuum and the desire to locate the signal conditioning electronics as close to the sensing element as possible. Consequently, the selection of the materials and assembly techniques used is critical and during development, leakage rates are measured by sophisticated residual gas analysis techniques.

One technique that may be used on certain sensor types is electrostatic bonding, whereby a high voltage ($0.3-1.2\,\mathrm{kV}$) is applied between the silicon and an ionically conducting glass substrate at a pressure of $0.2-0.4\,\mathrm{Nmm}^{-2}$ and a temperature of $350-500°\mathrm{C}$. This causes ions to migrate between the surfaces to form a hermetic seal and can be used at the wafer rather than just device level. The speaker concluded with the observation that "*Packaging has become a critical process, controlling the performance and cost of next generation automotive sensors based on micromachined silicon*".

The test and condition monitoring of MEMS devices was the topic of a presentation by a speaker from Lancaster University. Various MEMS devices were described, including pressure and acceleration sensors, micro-motors and micro-mirrors, and the key benefits of the technology were identified as:

- Economics of manufacture;
- High reliability (silicon's excellent mechanical properties);
- Improved performance (electronics part of, or close to, the sensing element);
- Low unit cost;
- Prospects for new applications.

However, it was pointed out that, despite the above and the huge amount of research into this technology, only three MEMS devices are yet in full-scale, high volume production: silicon accelerometers, pressure sensors and ink jet heads.

The trend in the automotive industry is towards distributed system intelligence and this requires the development of smart sensors and actuators. Reliability is vital and testing such devices was highlighted as a critical area. It was stated that, for an ASIC, test constitutes around 31 per cent of the total cost but for a silicon sensor, this figure is in the order of 44 per cent. This highlights the need for self-testing techniques that can be incorporated into the sensor itself. A good example is the silicon accelerometer, where the output can be measured when a test voltage is applied which causes the sensing

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structure to deflect as it would under the influence of acceleration. The speaker concluded by discussing attempts to develop various failure mode and effect methodologies using finite element analysis to model electrical and mechanical failures.

The sensor requirements of the Foresight Vehicle Programme were discussed by a speaker from.TWR (Tom Walkinshaw Racing). This is a UK government programme concerned with future vehicles and transport systems and attempts to generate a vision of these up to the year 2020. It comprises several themes, including sensors, as shown in Table II.

Whilst much of the presentation concerned the programme itself and more general technological themes, some anticipated sensing requirements were mentioned. One family of novel sensors for which a need may ultimately arise are associated with vehicles powered by fuel cells. Examples include a sensor to detect trace levels of CO in the hydrogen fuel and another to measure the conductivity of the cooling fluid in the cell, which has 300 volts applied across it. It was also suggested that future vehicle manufacturing processes may require the sensors to be installed to the body-in-white, therefore the sensors would need to withstand the harsh environment imposed by the painting and oven processes. More information on this programme is available at: www.foresightvehicle.org.uk.

All of the remaining five papers concerned specific sensor developments. A collaborative project involving BAe Systems and the University of Nottingham was the topic of a presentation by a speaker from the latter organisation and concerned multi-axis gyroscopes or "rate" sensors based on the vibrating ring principle. Single axis sensors already exist, including those based on microengineered $\langle 111 \rangle$ plane silicon. These rely on measuring the vibrating ring's position as its driven "carrier" mode is coupled to the response mode due to rotation-induced Coriolis forces. If the carrier mode amplitude is constant, then the response mode is proportional to the applied rate.

Table II Thematic groups of the foresight vehicle programme

Advanced structures and new materials (FASMAT)
Engine and powertrain
Hybrid, electric and alternatively powered vehicles
Telematics and advanced electronics, software and sensors
Design and Manufacture (DMaP)

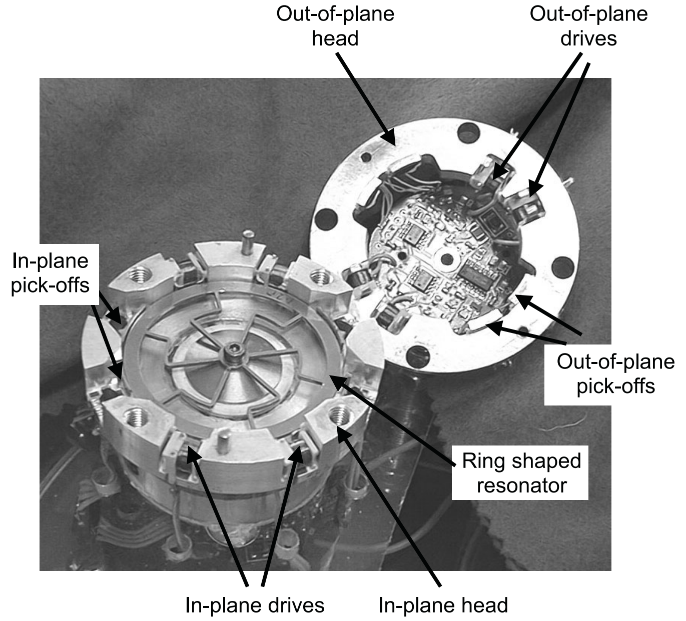
However, emerging market requirements are demanding multi-axis devices which could, for example, measure a vehicle's yaw rate (as used in existing vehicle stability systems) and also detect imminent roll and thus activate various safety features. Whilst it is possible simply to deploy two or more single-axis sensors, a multi-axis device would reduce overall size and cost and simplify the control electronics. The group has developed the theory governing multi-axis ring structure rate sensors and it can be shown mathematically that an in-plane carrier mode allows 3-axis sensing whilst out of plane carriers allow dual-axis measurements. The work at Nottingham involved the fabrication of a dual- rather than 3-axis device due to its relative simplicity and the fabrication was based on "macro-scale" technology rather than silicon micromachining because of timescales, costs and component availability. The sensor is illustrated in Figure 1 and has been shown to generate linear output signals when rate is applied in both the X and Y axis with little cross-axis interference. A 3-axis prototype is presently being tested and future work will concentrate on the fabrication of single- and multi- axis sensors based on silicon MEMS technology.

In contrast to the above, research at Cranfield University, in conjunction with the University of Nottingham, AEA Technology, the DETR and Transense Technology, concerns the development of a vibrational gyroscope which uses thin film surface acoustic wave (SAW) sensors. The principle is similar to the above but the rotation- induced changes in the vibration modes are detected by a pattern of SAWs, deposited on the surface of the structure. These sensors were used because:

- They can be produced by thin film technology and so minimise material cost;
- Have no moving parts, therefore the device will be rugged;
- Operation at high frequencies (~ 100 MHz) allows detection of lower frequency vibrations and DC stresses;
- Measure shift in resonant frequency, therefore high sensitivity possible.

Much of the research has focused on identifying the optimal SAW construction, materials and configuration, including 1- and 2-port resonators and delay lines. Ultimately,

Figure 1 Prototype electromechanical dual-axis rate sensor (reproduced with permission of BAe Systems and Nottingham University)

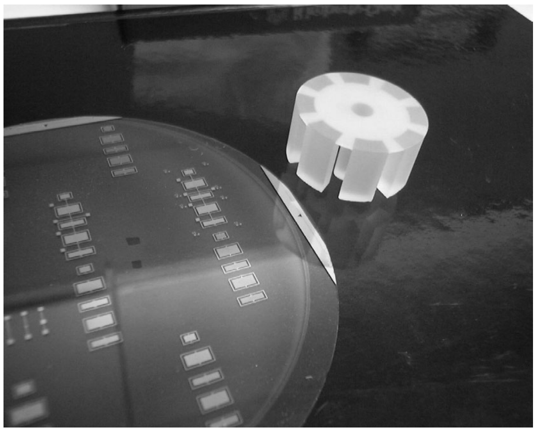


a 1-port structure was used as it offers a sharper response at the resonant frequency than a delay line and requires less complex electronics than a 2-port resonator.

The SAW comprised a piezoelectric zinc oxide (ZnO) layer, deposited by RF sputtering, gold electrodes and a quartz glass base. Various ZnO thickness were tried, ranging from 0.45 to 0.9 microns and with a continuous, rather than patterned, base electrode, the latter figure gave the best response. Figure 2 shows SAW resonators on a glass wafer and the gyroscope substrate. The SAWs will be interrogated remotely by a capacitive technique and the design of a suitable oscillator circuit is a priority for future work. Further work will also continue to optimise the materials used and ultimately SAWs will be fabricated and tested on a working device.

A presentation by a speaker from the University of Middlesex discussed new developments in automotive oxygen sensors. Solid-electrolyte oxygen ("lambda") sensors, based on zirconium oxide, are used on vehicles fitted with catalytic converters to hold the air/fuel ratio at, or close to, the stoichiometric point and thus optimise the combustion efficiency, minimise noxious exhaust emissions and protect the catalyst. They are also employed to control the exhaust gas recirculation (EGR) system in diesel engines by controlling the proportions of cooled exhaust gas and air. In view of their operating environment (in the exhaust

Figure 2 SAW resonators on a glass wafer and the glass gyroscope substrate being developed at Cranfield University



system) they need to be exceedingly rugged but also meet the stringent price restraints imposed by this industry.

Depending on the operating conditions, different types of sensors give the optimal performance: in excess air (lean) operation, amperometric types are best but when excess air and/or fuel-rich situations exist, double-chamber sensor types are desirable. The work at Middlesex has involved the development of a novel oxygen sensor based on planar thick film (TF) technology. It comprises an alumina substrate with a TF platinum heater on the back face (necessary to maintain the operating temperature of the electrolyte) and a solid zirconia electrolyte, sandwiched between inner and outer TF metal electrodes. The sensor has a diameter of only 8 mm, which, combined with the TF fabrication technique, should allow very low unit costs to be achieved. A university spin-off company, Sensox Ltd., has been set up to commercialise this technology. Figure 3 shows one of these sensors.

Figure 3 Thick film zirconia oxygen sensor

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A speaker from TRW Automotive discussed new driver assistance systems, including adaptive cruise control (ACC) and lane detection/departure warning systems. These require new types of non-contacting sensors such as 77 and 24 GHz radars, lidars and video cameras. The work at TRW has focused on the latter, as road features are designed to be highly visible and video can detect lane markings, as well as detecting other vehicles and pedestrians.

A lane detection system potentially offers a high level of functionality, i.e.

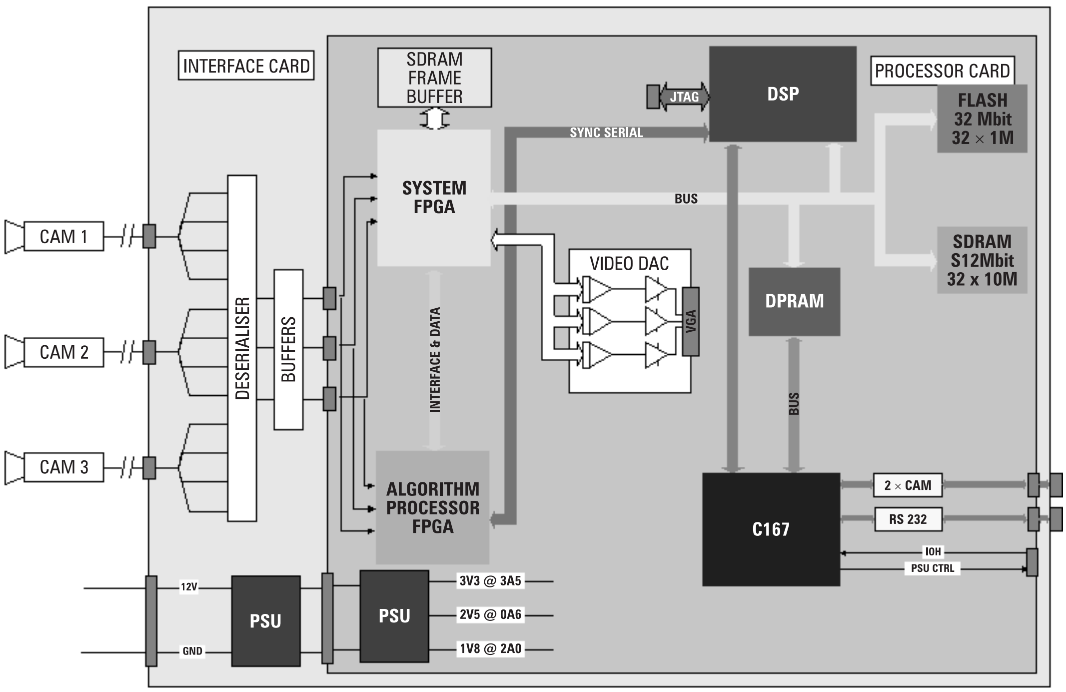
- Lane departure warning;
- Lane guidance;
- ACC target selection;
- Curve entry speed adaptation;
- Driver drowsiness monitoring;
- Adaptive headlights.

However, video-based systems require a great deal of complex signal processing, which adds considerable cost. TRW has been involved in this work since the "Prometheus" project which ran between 1990 and 1994, during which period a short- range, straight line lane detection algorithm was developed which ran on a custom twin Motorola 88110 CPU. During the "AC-Assist" programme which ran between 1995 and 1998, a curved lane algorithm was developed which could be run on a commercial Matrox C80 PC card and during 1999, internal developments by TRW have improved the curved lane algorithm which is now running on a normal PC.

"Carsense" is a three-year, EU collaborative project involving 12 partners which runs until 2003. The focus is on a forward-facing video sensor which will detect and analyse the environment ahead of the vehicle. TRW is responsible for the embedded image processing hardware, the algorithms and the data fusion. The hardware comprises three camera inputs, an 800 MFLOP DSP and a 300k gate FPGA, 2 CAN ports and a VGA output for debugging, as illustrated schematically in Figure 4. It is anticipated that this research will yield a low cost, high functionality, video-based system whose signal processing will be reduced to a three chip solution. In the longer term, vehicle data fusion systems may well incorporate inputs from radar, video, lasers, telemetry and GPS, leading to truly interactive vehicles.

Imaging using IR was the theme of a paper from IRISYS, a UK manufacturer of low cost IR sensing technologies. Using novel pyroelectric ceramic sensing technology, the company has developed inexpensive imaging systems which fill a gap in the market between 1–4 element devices, priced at around \$1 and typically used for intruder and flame detection, and sophisticated 10 k–100 k element array-based imagers which cost over \$1000.

Figure 4 Schematic of "Carsense" project video sensor system



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In contrast to CCTV systems, IR imaging requires less computational power, is immune to light variations and adverse weather conditions and needs minimal processing to achieve powerful detection and tracking algorithms. As such, it is inexpensive and well suited to several automotive applications. Some of those being considered include: traffic tracking and counting, typically from motorway gantries; traffic control; people counting at pedestrian crossings; blind spot detection; and uses in safety systems where the position of the occupants must be accurately measured prior to the deployment of the airbag.

Overall, this event gave a broad and reasonably well balanced overview of development in automotive sensors. In particular, it highlighted the critical need to achieve high performance at very low costs, combined with protection against an often extremely harsh operating environment.