CHEMICAL MICROSENSORS: A NEW GENERATION OF ELECTRONIC DEVICES?

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Developments in solid-state sensors and signal processing are changing the face of measurement and control technology. Small, cheap, robust and reliable, the new microsensors will find applications ranging from washing machines to industrial plant control.

In the past decade there has been considerable interest in the development of electronic devices capable of measuring a wide variety of chemical properties. Recent advances in integrated circuit technology have enabled very small sensors to be produced for control and analysis of many industrial and medical applications. The advantages of this form of fabrication are manifold — small, highly complex electronic devices can be modified to provide sensitivity to various chemical species and can be manufactured in very large quantities. However, until very recently there has been a lack of willingness to exploit these developments commercially because of problems associated with signal processing and interfacing to control systems. These difficulties can be overcome by using advanced digital techniques which now enable existing sensor technology to be used in exciting new applications.

A major problem with most chemical transducers is that of contamination. In many applications, the devices are required to operate in hostile environments where there may be a large number of interfering chemical species which degrade the sensor performance either by reducing sensitivity or by producing spurious signals. This is further complicated by any nonlinearity or drift present in the sensor itself. These factors have in the past made the choice of practical sensors very limited: promising mechanisms and materials have had to be rejected due to difficulties in achieving a ‘useful’ electronic output.

By careful signal conditioning, these problems may be overcome; surprisingly, this aspect until recently received little attention compared with the effort put into the design of the sensing elements themselves. Analogue processing of low-level, noisy signals can be complicated and costly, but the advent of relatively cheap, high-power microprocessors has made it possible to perform this function using extremely sophisticated, high-precision digital techniques which are inherently more reliable.

FET-based sensors

Of the wide range of solid-state devices which may be employed for chemical sensing, the most promising is perhaps the field effect transistor (FET), the
composition of which may be altered to enable the
detection of different chemical species.

Several different types of FET-based chemical sen-
sors, including a variety of gas detectors (GasFETs),
ion-sensitive devices (ISFETS) and humidity sensors,
have either recently been introduced to the market-
place or are likely to become commercially available
within the next two years. Other devices for analysis
of more ‘exotic’ (e.g. biochemical) species are ex-
pected in the slightly more distant future.

The gas-sensitive devices are very similar to the
standard MOSFET used in conventional electronic
circuits, with two exceptions. The normally inert
gate electrode is replaced with a catalytically active
metal such as palladium or platinum, as shown
schematically in figure 1, and the finished chip is not
hermetically sealed but left open to the surrounding
environment. These modifications enable the detec-
tion of small concentrations of hydrogen (Pd gate)
or ammonia (Pt gate) in the ambient by the change
in FET characteristics resulting from chemisorption
of the gas at the surface of the gate electrode.

For an FET operating in the saturated region, the
drain current $I_D$ is related to the gate and threshold
voltages, $V_G$ and $V_T$, by the expression

$$I_D = (W/C \mu L) (V_G - V_T)^2,$$

where $W$ and $L$ are the conduction channel width
and length respectively, $\mu$ is the charge carrier
mobility and $C$ is the capacitance per unit area of the
gate insulator.

Figure 1. Schematic cross section of an n-channel GasFET
device.

The source and substrate are connected to
ground, and the gate and drain to a constant current
supply. The presence of a reagent gas causes
a change in the threshold voltage of the device which
may be measured by monitoring the gate voltage.
The response of a Pt-gate GasFET to ammonia gas is
reproduced in figure 2: (a) shows the change in
threshold voltage for varying gas concentration, and
(b) the transient response to 100 ppm ammonia.

A number of different gate compositions have

Figure 2. (a) Ammonia response characteristics of a Pt-
gate GasFET: (b) transient response of a Pt-gate GasFET to
100 ppm ammonia.
Table 1. Specifications of hydrogen and ammonia GasFET devices.

<table>
<thead>
<tr>
<th></th>
<th>Hydrogen</th>
<th>Ammonia</th>
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<tbody>
<tr>
<td>Range (ppm)</td>
<td>1–1000</td>
<td>1–1000</td>
</tr>
<tr>
<td>Response time (to 90% final reading)</td>
<td>&lt;10 s</td>
<td>&lt;15 s</td>
</tr>
<tr>
<td>Accuracy</td>
<td>±10%</td>
<td>±10%</td>
</tr>
<tr>
<td>Operating temperature range</td>
<td>-40–+250°C</td>
<td>0–90% RH</td>
</tr>
<tr>
<td>Operating humidity range</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Operating life</td>
<td>&gt;3 years</td>
<td>&gt;3 years</td>
</tr>
<tr>
<td>Cross sensitivity</td>
<td>Hydrogen sulphide</td>
<td>Hydrogen sulphide</td>
</tr>
<tr>
<td>Chip dimensions</td>
<td>0.8 mm×0.8 mm</td>
<td></td>
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<tr>
<td>Packaging</td>
<td>Standard 8-pin TO5 header</td>
<td></td>
</tr>
<tr>
<td>Sensor power requirements</td>
<td>400 mW</td>
<td>400 mW</td>
</tr>
</tbody>
</table>

been developed in order to detect selectively and accurately the presence of a variety of gases including hydrogen, ammonia, hydrogen sulphide and various hydrocarbons, down to concentrations as low as one part per million – table 1 gives the specifications for commercially available hydrogen and ammonia GasFET sensors. New catalytic materials are continuously being investigated and tested in order to further extend the range of detectable gases.

Recent refinements to the basic GasFET design have resulted in the device pictured in figure 3, which comprises the gas-sensitive FET together with an additional FET with a gate electrode of a chromium–gold alloy. This is used as a stable inert reference to compensate for aging effects and baseline drift. A pair of heating elements (diffused resistors) and a temperature-sensing diode structure are also incorporated to enable the device to be operated at a precisely controlled elevated temperature. This significantly reduces the time taken for the sensor to respond to the presence of the selected gas.

Applications

The potential applications of GasFET are numerous. Fire detection systems which use a hydrogen sensor are able to detect the early stages of combustion. Similar devices have also been used to monitor the degree of corrosion in fluid pipelines by analysing the minute amounts of hydrogen liberated during the corrosion process; this can lead to considerable savings in plant downtime and costly repair bills. Another novel application which has provoked some interest is the use of an ammonia-sensitive device as a means of protection against electronic component overheating. A specially formulated urea-containing paint is sprayed onto finished circuit boards, coating the components thoroughly. At a particular temperature (dependent upon the precise composition of the paint), the coating undergoes thermal decomposition which liberates ammonia which can be detected by a platinum-gate GasFET. The principle of operation is shown in figure 4. The advantage of this system is that the overheating of a single discrete component can be detected immediately and a warning condition indicated, so that remedial action (such as switching to back-up circuitry or system shutdown) can be taken before component failure occurs. This has obvious applications in high-reliability and high-performance environments (e.g. military, medical, aerospace) where such failure could be very costly in financial or possibly even human terms.

Other GasFET devices have uses in the automotive industry for exhaust gas monitoring, in consumer products (for example, detectors for gases evolved in conventional and microwave cooking, humidity sensors in washing machines and dishwashers etc), for environmental monitoring and control, and obviously as domestic and industrial gas-leak detectors.

Ion-selective FETs are different in construction from the basic GasFET structure described above in that instead of a metal electrode an active membrane is deposited onto the gate insulator region and the device immersed in an aqueous solution (figure 5). The membrane is such that it will support the exchange of a specific ionic species, changing the electric potential at the solution–membrane interface. The electrical characteristics of the device are therefore directly influenced by the ionic concentra-
tion of the solution. As the ISFETS are physically small compared with conventional ion-selective electrodes, they offer a considerable advantage due to the small volume of analyte required, and thus are advantageous for use in a clinical environment for blood analysis. Commercially available ISFET devices are pictured in figure 6.

We can see from these few examples why there is currently such great interest in the field of sensor development. The importance of this technology is marked by the increased research activity worldwide and is clearly demonstrated by the number of new conferences on transducer science which have been inaugurated in the last three years. The commitment of industry to commercial sensor development has led to the formation of businesses such as THORN EMI Microsensors, a venture company set up within the Central Research Laboratories to investigate potential applications and markets for advanced sensor products. The company is already selling hydrogen and ammonia sensors and dual-function (pH and sodium) ISFET devices for customer trials.

**Signal processing**

Solid-state chemical sensors offer many intrinsic advantages over conventional types of transducers.

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**Figure 4.** Principle of operation of sacrificial coatings system for electronic overheating protection.

**Figure 5.** Schematic cross section of an electroactive ISFET.

**Figure 6.** Some commercial ISFET devices.
They are inherently more rugged and potentially far cheaper, provided suitable high-volume applications can be identified which enable large-scale fabrication techniques to be employed. However, what has prevented the exploitation of this technology is not any lack of research into sensor materials and devices so much as the limitations of conventional electronic circuitry. Complex signal conditioning is required to overcome the problems associated with the nonlinearity and drift of the sensor element in order to make accurate measurements. Moreover, it is essential in many applications to be able to interface the sensors to monitoring or control systems. This cannot be achieved using discrete components without very complicated circuits which are difficult to design and test, which tend to be somewhat power-hungry, and which are physically large. Developments in recent years in the field of circuit miniaturisation and in the use of microprocessors for signal processing have completely changed the face of sensor technology. Instead of the traditional analogue signal acquisition circuitry, extremely sophisticated processing functions can be implemented very cheaply and with the added benefits of being very reliable, more compact, and relatively simple to interface with digital control systems.

The size and cost of the supporting electronics may be reduced considerably by incorporating this circuitry into the sensor module itself. For example, by making use of thick-film hybrid technology the electronic circuitry which is typically required for output signal conditioning and temperature control of a standard GaSFET device can be reduced from some 19 cm×11 cm×6 cm (discrete components assembled on printed circuit boards) to as little as 3.8 cm×1.3 cm (film technology module with integral sensor chip); this comparison is demonstrated by the conventional and hybrid realisations of the circuit pictured in figure 7. This design has the advantage of having the active GaSFET chip physically close to the support electronics, thus avoiding the problems of noise and signal attenuation associated with long interconnects. Another obvious benefit is the greatly reduced size of the complete sensor system, which will make remote deployment far easier. Possible extensions to the circuitry are being investigated, such as the development of a multi-sensor distributed system in which each individual sensor can be uniquely interrogated by a central controller, either by a dedicated communication interface or by mainsborne telemetry (i.e. by utilising the standard mains wiring as a signal link). This would be invaluable for environmental or security monitoring of large installations because of the flexibility and performance offered by such a system.

On-board microprocessors

This concept can be taken one stage further by introducing a microprocessor into the sensor module to give more processing power at the data acquisition level of distributed systems. This possibility produces the system designer’s first dilemma: what degree of intelligence is required at the ‘front end’? The different configurations of such a system are shown in figure 8. Option 1 denotes the traditional way of using separate conditioning and converting stages to interface an analogue sensor output with a microprocessor for additional signal processing. Steps have already been taken to incorporate some of this circuitry into the sensor unit itself (option 2), such as the thick-film hybrid device described earlier, to gain the benefits of reduced size, shorter signal paths, fewer solder joints and higher reliability. As these circuits will be fabricated from silicon, it is even more advantageous to implement them in the same chip as the basic sensing element. Although the added complexity will result in lower device yield and thus increase the price of the sensor, the overall cost of the system will be lower due to the savings in additional components, assembly and test time. There is also current interest (the NERI Microsystems government initiative is a good example) in silicon hybrids – integrated circuits mounted on a silicon substrate which has predefined active devices incorporated. This permits the reduction of circuit size without the need for the substantial commitment of both capital and personnel which is necessary to support the design and production of on-chip electronics.

Additional active devices may be added at this stage to compensate for errors introduced by secondary properties (such as interfering chemical spe-
cies, humidity, temperature) or to measure more than one parameter. Such multiple sensor arrays can be developed for specific applications where higher selectivity and accuracy are desirable. However, the market for ‘tailored’ devices is by definition limited, and the cost is unlikely to make them commercially viable unless a high-volume application can be identified.

Because of the greater flexibility and improved data-transmission characteristics offered by digital signal processing, the majority of transducer systems are likely in the future to make use of these techniques. Incorporating a degree of intelligence and independence at the remote signal-acquisition level means that centralised control processors will receive pre-engineered data which can be analysed and acted upon more quickly than can the ‘raw’ signals generated by sensors at present. In this way, more time is made available for important report generation and system management tasks. This may be accomplished by adding an analogue-to-digital convertor and microprocessor to the rest of the circuitry in the sensor module. Although it is quite possible to incorporate digital processing functions on-chip, manufacturers are again unlikely to take such a large step until a single, large-volume application occurs which demands such an expensive product. In the meantime, they will undoubtedly look towards microprocessor support circuitry as ‘add-on’ hardware, perhaps incorporated in the sensor module, to interface with a remote host controller.

The advantages of having an on-board microprocessor in the transducer housing are manifold: the system designer has far greater control over the acquisition of data from the sensor and can use the enhanced processing functions for signal linearisation and mathematical manipulation, compensation of secondary parameters, multiplexing sensor outputs, autocalibration, digital filtering – the list is endless.

Unfortunately, and with some justification, the use of microprocessors in intelligent sensor systems is viewed by some with suspicion. There is a great temptation to use a microprocessor purely for its own sake or as a ‘selling feature’ (marketing departments kindly note!), whether or not it is really necessary to make accurate measurements. It must be remembered that the use of a microprocessor involves a substantial amount of extra work on the part of designers and test engineers to develop and debug the hardware and software required to produce reliable results: unfortunately this is all too quickly forgotten in the enthusiasm to produce the ‘ultimate’ instrument. For simple applications, conventional analogue circuits will generally suffice – only when the performance of a device or system will be significantly improved by utilising the power and versatility offered by a microprocessor is the additional cost really justified.

A revolution in instrumentation

From the above considerations it can be seen why the recent developments in sensor technology and digital signal processing have provoked such a degree of excitement and activity in both academic and industrial research establishments. In the next five years, the commercial availability of small, cheap, compensated sensors which are both robust and reliable is expected to revolutionise the field of instrumentation. Such devices will be found in a wide range of applications, from the humble humidity sensor controlling a washing-machine cycle to the multiple distributed system of intelligent transducers executing complex plant control and monitoring tasks.

Many users, entrenched in the traditional approaches to measurement techniques, have been slow to accept and implement these latest advances. New companies entering the sensor business to develop novel devices for specific applications and brand new product lines may accelerate the change, and consequently may reap the rewards from this fast-moving technology.

Further reading