Sensing new applications for CMOS

CMOS technology is set to enable a new range of sensor devices, with applications in a wide range of sectors. By **David Boothroyd**.

A pivotal moment in the development of the semiconductor industry came in 1963, when two researchers from Fairchild – CT Shah and Frank Wanlass – presented a conference paper that described logic circuits in which p- and n-channel MOS transistors were combined in a 'complementary' symmetry configuration. The approach, patented by Wanlass, used virtually no power in standby mode and came to be known as CMOS. The rest, as they say, is history.

CMOS became the dominant fabrication technology for the VLSI era, with billions – probably trillions – of chips produced using it. But most of these have been processors. Now, we are on the verge of a new CMOS era, but one in which CMOS ICs are increasingly being developed for something quite different – sensing.

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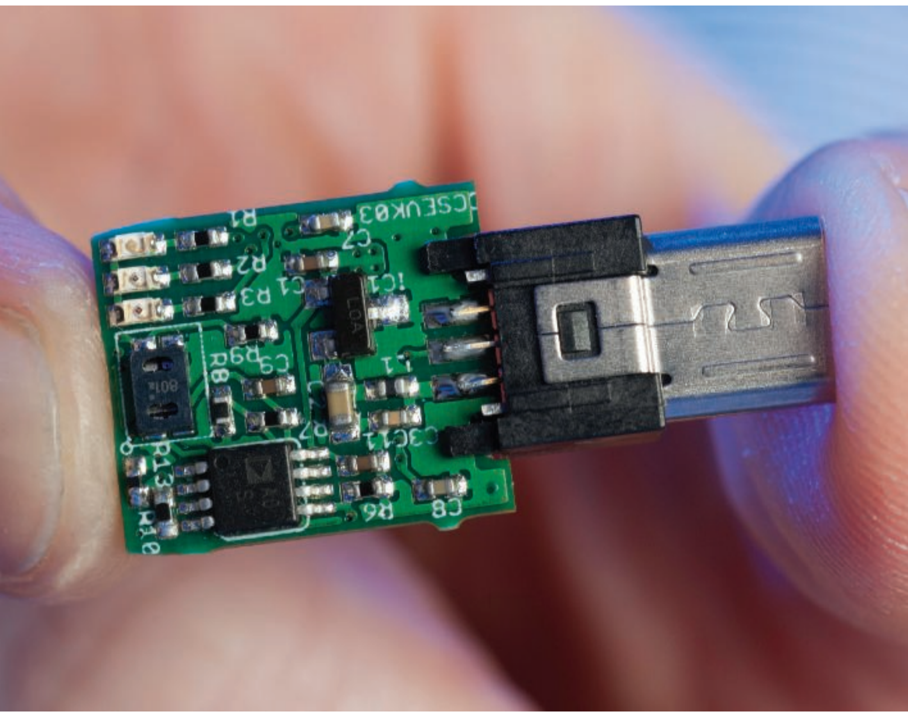

CMOS sensor chips has already been a major success story in imaging, with millions of digital cameras now using them. But CMOS sensors are increasingly being seen as ideal devices for many other sensing applications.

One company aiming to exploit this opportunity is Cambridge CMOS Sensors (CCS), founded in 2008 as a spinoff from work done at Cambridge University. One of the founders is Florin Udrea, a Professor of semiconductor engineering at the university, who has formed previous spinoff companies, such as CamSemi, a developer of energy efficient power ICs. Another member of the management team is chief scientist Julian Gardner, a Professor of electronic engineering at Warwick University.

At the heart of CCS' products is MEMS based micro hotplate technology, which makes it possible to produce sensors for applications ranging from environmental and automotive to consumer and healthcare.

The micro hotplate allows an area on the device to be heated to as much as 1000°C in less than 25ms. Originally, this was used to create a source of IR light. But,

Because its technology requires very little board space, left, CCS envisages its sensor technology being incorporated in smartphones to monitor, for example, indoor air quality. Photograph: Charlie Milligan

by using the same device and by adding electrodes and a suitable sensing material, heating the hotplate can create a chemical reaction between the sensing material and a particular gas.

"For example, the metal oxide (MOX) sensing material we use for carbon monoxide is very reactive at 160°C. Resistance drops as a result and, by measuring that, we can calculate the concentration of the target gas in the environment," says Paul Wilson, CCS' marketing and applications director. "Much the same applies at different temperatures with substances like ethanol (240°C) and volatile organic compounds (VOCs, 300°C)."

Key to the whole concept is that the micro hotplate is made using a standard CMOS process, which not only makes it eminently scalable for high volume production, it also means the sensing process can be repeated many times. It also makes for low cost, which makes it economically practical to build arrays of sensors. Other advantages – hallmarks of all CMOS sensors – include low power consumption, embedded intelligence and an ultra small form factor.

One application for these devices could be multipurpose sensors that can monitor indoor and outdoor air quality. CCS is currently working on a four sensor array, which could also have a built-in digital interface for connection to many different platforms.

"Conventional MOX gas sensors have been available for decades, but they have typically been quite large, demand high power, their performance drifts over time and they are not inherently scalable to mass production – millions of units – as CMOS devices are," Wilson explains. "Our key innovation at CCS is developing the deposition process – putting the MOX sensing material on top of the silicon, then packaging and testing it, all with the aim of making it feasible to use such sensors in really high volume applications."

One such application CCS is targeting is putting a CMOS gas sensor into smartphones or tablets, even wearables, with products possibly appearing in 2015. This would enable the user to monitor indoor air quality, for instance, with an alarm warning them of too high a level of carbon monoxide. Another possibility for a wearable gas sensor would be to detect acetone levels on an individual's breath, important in monitoring their breakdown of fat. The IoT (Internet of Things) market is also seen as a potentially huge opportunity for CMOS sensors.

Automotive applications

CCS is anticipating a host of other potential applications: in the automotive industry, examples include an alcohol detector, monitoring in-vehicle air quality and emissions testing and monitoring; for domestic and industrial markets, think gas detection in smart meters, spotting fridge leaks, or alarms for fire or smoke; and medical and healthcare, through breath analysis.

Arrays of different sensors react to the VOCs contained within odours where the pattern of the response from the sensors is used to 'fingerprint' that odour. This technique has been demonstrated in electronic nose devices for bio-sensing, an application for which its sensors are ideally suited, CCS says. Combining these various uses is the future, Wilson believes.

"I do see more and more collaboration between various companies to create universal sensors that are tied to specific data. For example, if you can correlate environmental data like air pollution to your GPS, that could be useful. Or connecting air quality sensing to wearable health monitoring devices. The ultimate goal is to make this type of sensor functionality so compelling that consumers want to use it on a daily basis."

One potentially major field is low cost CMOS biosensors in biology and medicine. Tony Graham, a researcher at Bath University's Department of Electronic and Electrical Engineering, has examined the commercial potential for CMOS in the biosensor field, especially in neuroscience. It will be a major market, but there are hurdles.

"The adaptation of standard CMOS IC technology as a transducer in cell-based biosensors in drug discovery pharmacology, neural interface systems and electrophysiology requires electrodes that are electrochemically stable, biocompatible and affordable," he says.

Unfortunately, CMOS does not meet the requirement for electrochemical stability. For devices intended only for research, CMOS can be suitably post-processed to get over this problem, but this can be quite expensive. For commercial biosensors, the economies of scale that CMOS brings means the cost of any post processing must be minimised.

However, the materials used in the CMOS process – specifically, aluminium and its oxide – raise problems with its use in biosensors; in particular, the interface between the analyte (the substance being tested) and the electrode interface. There are also potential issues of neurotoxicity.

"This is generally considered to be the main roadblock to CMOS biosensor commercialisation," Graham says.

But the potential is clear. That is because several electrochemical techniques are used for biosensing: amperometric (measuring current), conductometric (changes in electrical conductance), potentiometric (electric potential), and impedimetric (impedance). All these can be integrated using CMOS circuits adjacent to the transducer, with electrodes in contact with the analyte operating actually on the surface of the IC.

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This requires something of a change in practice, because CMOS processes have always been purposely developed to be closed to the surrounding environment to avoid contamination problems, which cause low manufacturing yield and poor reliability.

"Opening the chip surface to form a transducer is somewhat inconsistent with the goals of most semiconductor manufacturers," Graham admits.

Nevertheless, one area of great interest for CMOS sensors is in neuroscience.

"In this case, the multiple electrode array (MEA) could be a simple transducer element used to sense the action potentials of neurons, or could be part of a cell-based biosensor if the neuron is acting as a bioreceptor, for example, for high throughput drug screening," Graham adds.

The work underlying the development of MEAs began in the 1990s with the realisation that planar semiconductor technologies, primarily CMOS, offered a potentially cheap source of electrodes, integrated signal processing and increasingly excellent spatial resolution. Early investigations by groups such as the Max Planck Institute of Biochemistry identified the adherence of biological cells to the IC electrodes as a potential major challenge – and they have been proved right.

"Progress has been slow as the factors influencing cell-substratum adhesion are complex," Graham notes.

Even so, advances are happening. One leader in the MEA market is Swiss company 3Brain, which has developed one of the first CMOS MEAs. Its APS-MEA chip uses CMOS to form an array of 4096 electrodes for high spatial resolution electrophysiology. APS stands for Active Pixel Sensor, reflecting the fact that active signal processing takes place locally at the electrode level. 3Brain says it has achieved a high degree of integration by locating an amplifier/filter-circuitry underneath each individual electrode.

"This concept originally stems from the technology of CMOS-based optical cameras, where the light sensitive elements are replaced with metallic electrodes," it says. "CMOS technology can bridge the gap between low electrode count MEA devices and high resolution MEA platforms. CMOS allows cost efficient implementation of electrodes and electronics onto a single silicon chip."

The result is that no more complex interconnection is required to take low amplitude signals from the electrodes to an external bank of amplifiers. The amplifiers are directly integrated underneath each electrode, allowing the implementation of MEA devices with thousands of electrodes without increasing the interconnection complexity. On-chip switching – multiplexing – makes it possible to route hundreds of electrode channels to one output.

Another Swiss company producing CMOS sensors is Sensirion, which uses its CMOSens technology to create sensors for applications like humidity and liquid flow sensing. The latter demonstrates the major benefits CMOS sensors can bring: Sensirion says it has created a digital sensor for liquid flow that is 100 times faster, 10 times smaller and 25 times lighter than previous conventional flowmeters.

Sound sensing is another application where CMOS is used, for example by Akustica in its MEMS microphones. These are monolithic devices with the mechanical functionality of the microphone integrated with analogue and digital electronics all on the same silicon die.

"Unlike other MEMS manufacturing technologies, CMOS MEMS employs standard CMOS processes to fabricate microstructures within the metal dielectric layers that are deposited during the standard CMOS processing flow," it says. This results in mechanical structures only microns away from the analogue and digital electronics, creating the world's smallest MEMS microphones, Akustica says.

Graham says more innovative CMOS sensing products are in the pipeline, with examples like a DNA sequencing chip from Life Technologies, although this will require additional layers to be deposited on the top of the CMOS and patterned using photolithography to provide biocompatibility. Similarly, CustomArray uses CMOS in its DNA synthesis chips, where the electrode array is formed using photolithographic post processing. But even though the need for post processing adds to cost, it could play an important role in widening the scope of CMOS biosensors still more, Graham says.

"The adoption of suitable IC post-processing may foster the commercialisation of CMOS cell based biosensors in drug discovery, neuroprosthetics and environmental applications and enable affordable research tools for bioscience."