AIR QUALITY S

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A CO_2 sensor has been developed for specialist applications in air quality monitoring and control, offering good long-term stability, high selectivity, and a low humidity dependence.

The concentration of CO_2 can be used as a good indicator of air quality in the office or in the home. Until now, an obstacle to the widespread adoption of control systems based on CO_2 concentration measurement has been the lack of stable, accurate and yet economical sensors for this unreactive gas. Now, however, with the introduction of new solid electrolyte sensors, rapidly-reacting measurement systems for air quality control can be produced. The concentration of CO_2 in fresh air is generally around 350 ppm (parts per million), although this is of course subject to variations due to natural as well as artificial causes. These variations are nevertheless of low amplitude and take place over long periods. In inhabited living and working spaces the CO_2 concentration can quickly rise to many thousands of parts per million as a result of respiration, smoking for other reasons. **Figure 1** shows the evolution over time of CO_2 concentration in a test room holding between 10 and 80 people. Of course many other substances have an influence on air quality (and in particular on the perception of odours). Research has shown, however, that CO_2 is the key indicator for determining air quality. Subjective perceptions of air quality certainly correlate with a gradual rise in the level of CO_2, especially bearing in mind that CO_2 is an odourless gas. If one goes into a room with a high CO_2 concentration, one immediately feels the need for fresh air (the so-called 'meeting room effect'). **Table 1** shows the effect of various levels of CO_2 on humans.

A range of sensor technologies

The most widely-used technique for CO_2 measurement is by NDIR (non-dispersive infra-red) absorption. This exploits the physical property of CO_2 that it absorbs infra-red light at a wavelength of 4.27 µm. The CO_2 partial pressure can be measured very selectively and accurately using this method (especially in the case of high absolute concentrations of CO_2, even up to 100 %). Unfortunately, for measuring lower concentrations a long optical path through the gas is required in

ENSOR New CO_2 sensors for air quality monitoring

order to obtain a sufficiently significant absorption effect. The infra-red method is stable over long periods of time and has no moving parts. It is, however, bulky and requires precision optics and is therefore correspondingly expensive.

There are a few CO_2 sensors employing liquid electrolytes on the market. A decisive disadvantage of these cells is their limited life, the poor stability of their outputs and hence the lack of reproducibility of readings. There is also a general risk of leakage with cells that contain a liquid: this can lead to damage to the sensor or to nearby components. These sensors have therefore not been used in ventilation control systems.

Certain solids possess the property that ions can move within them. This makes them ideal to function as the electrolyte in a gas sensor. Particularly well suited to detecting gaseous oxides such as CO_2 or NO_x are materials based on a natrium (i.e., sodium) super-ionic conductor, or NASICON, structure. NASICON materials, which have been known for some time, are ceramics capable of conducting sodium ions. The chemical formula is $Na_{1+x}Zr_2Si_xP_{3-x}O_{12}$, with $0<x<3$. The highest ion conductivity is exhibited when $x=2$. Many studies have sought to find an arrangement whereby an electrochemical cell is constructed from NASICON material together with chemically active layers, giving an electrical voltage which depends on the ambient gas concentration. The principal obstacle to commercial mass production was the lack of stability and reproducibility of the solid electrolyte CO_2 sensors, and their high humidity dependence. The Japanese semiconductor gas sensor manufacturer Figaro has now managed to develop a process for making long-term stable CO_2 sensors as standard components with reproducible properties and low humidity dependence.

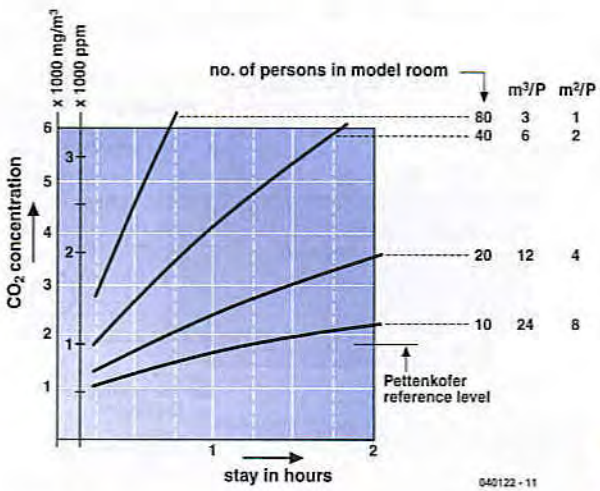


Figure 1. CO_2 concentration in a 240 m^3 test room.

% by volume	Concentration
0.022	Concentration in air in glacial ice from 18000 years ago
0.026	Concentration worldwide in pre-industrial age (before 1850)
0.035	'Fresh air' concentration today, rising by approximately 0.5 ppm per year
0.04	Onset of noticeable effects indoors: cranial pressure, feeling of stuffiness
0.07	Concentration in open air in cities
0.08	Heightened olfactory sensitivity
0.1	Maximum value according to Pettenkofer (1858)
0.14	Urban air in dwellings, maximum value for office buildings
0.3	Peak concentration during Dortmund bunker occupation experiment (1964)
0.4	Maximum value in classroom after lesson
0.5	Maximum workplace concentration: 5000 ppm or 9100 mg/m^3
0.7	Maximum value in cinema after film
2.0	Physiologically tolerable value for short periods
2.5	Intoxication-like effects on divers
3.0 to 4.0	Increased difficulty breathing
4.0 to 5.2	Exhaled air
5.0	Mixed with oxygen (95%) for use in artificial respiration apparatus
6.0 to 8.0	Paralysis effects similar to those of curare
8.0 to 10.0	Lethal dose if inhaled for long periods
10.0	Extinguishes a candle
~10.0	Blood concentration in marine mammals
~10.0%	Short-term maximum value in artificial CO_2-bath air, lethal if inhaled for even a short period

Table 1. CO_2 concentrations (0.03 % by volume = 300 ppm)

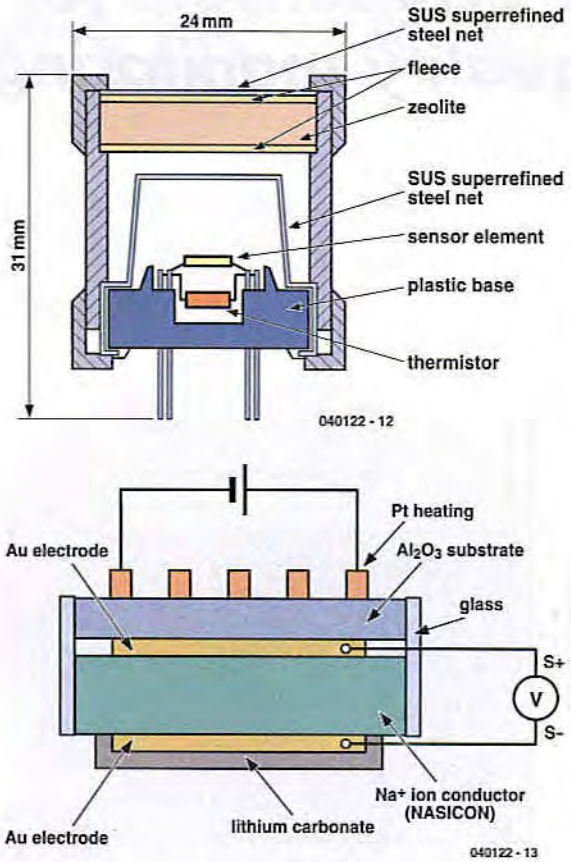


Figure 2. Cross-section through the TGS4160 and the sensor element itself.

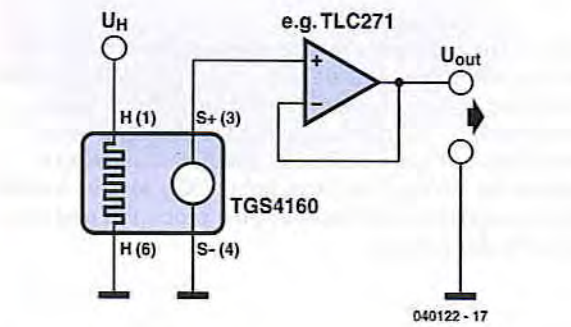


Figure 3. The sensor element must be connected to an extremely high-impedance input circuit.

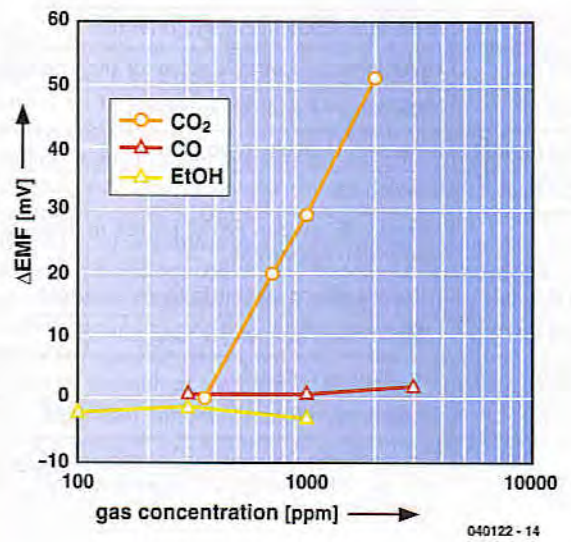


Figure 4. CO_2 sensitivity of the TGS4160 (and insensitivity to CO and ethanol)

The TGS4160 gas sensor

The TGS4160 consists of a CO_2-sensitive solid electrolyte cell with an internal thermistor for temperature compensation. Figure 2 shows the construction of the sensor and a cross-section through the sensor element. A NASICON disc with a diameter of 4 mm and a thickness of 0.7 mm is printed with gold electrodes on each side. A layer of lithium carbonate (Li_2CO_3) is added on the cathode side and then calcined at 600 °C. A thin disc of aluminium oxide ceramic, carrying a printed platinum heating element, is laminated onto the anode side. The edges of the sensor are sealed with glass. Platinum wires are bonded to the sensor element and spot-welded to the connection pins on the sensor base. The sensor base is made from glass fibre reinforced polybutylene terephthalate, and over it a mounted a two-layer stainless steel mesh as a flame retardant. The external enclosure is made from reinforced polyamide and includes a zeolite adsorption filter to prevent ingress of interference gases such as ethanol.

Signal conditioning

For good sensor performance and long life it is important to measure the cell voltage using as high an impedance as possible. The cell has a high internal resistance and so a low impedance measurement would give a false reading, and furthermore a significant external current would flow, causing a continual flow of ions in one direction. Over a long period this would damage the sensor. The input impedance of the measurement circuit should therefore be at least 100 MΩ and the bias current should be less than 1 pA. A typical basic circuit is shown in **Figure 3**.

The output EMF is relatively stable as long as the sensor is heated. Long unheated storage, however, especially at high humidity, can lead to a significant drop in EMF. Nevertheless, the difference EMF (ΔEMF) between the value at 350 ppm CO_2 and the value at higher atmospheric CO_2 concentrations remains very stable. The ΔEMF of the TGS4160 shows a linear dependence on the logarithm of the CO_2 concentration (**Figure 4**) and only at higher humidities (over 60 %) does it start to show a slight humidity dependence. Because of these properties, the sensor is suitable for use in rapidly-reacting CO_2 air monitoring systems.

Because of the drift that can occur, the sensor is not suitable for measuring absolute CO_2 concentrations, but only the CO_2 concentration relative to the 'natural' concentration in fresh air. Special signal conditioning is thus required on the cell output voltage, which is carried out in software using a dedicated microcontroller running an application-specific algorithm (**Figure 5**). To evaluate the ΔEMF the reference level corresponding to 350 ppm CO_2 must first be determined. To do this we assume that the natural concentration of CO_2 in fresh air never falls below 350 ppm and that there will be fresh air in the measured environment at least from time to time. Given these assumptions we can take the highest EMF measured over a specified period (of say 24 hours) to be the reference EMF for 350 ppm. If during a 24 hour period the current reference level is not reached, the algorithm automatically reduces the stored reference value by a set amount, until the measured EMF once again exceeds the stored reference value. In this way a drift in either direction is automatically compensated for: the measuring system is self-calibrating.

Principles of operation

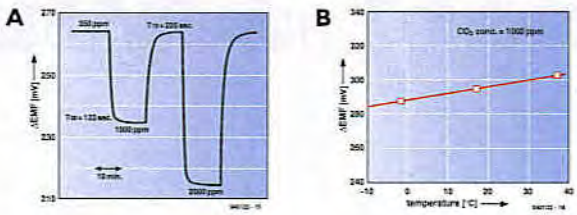
The sensor element is heated to about 450 °C by the heating element. The equilibrium point of the cathode reaction depends on the CO_2 and O_2 partial pressures. The cathode reaction is as follows:

$$2Li^+ + CO_2 + {}^1/_2\,O_2 + 2e^- \Leftrightarrow Li_2CO_3$$

and the anode reaction is:

$$2Na^+ + {}^1/_2\,O_2 + 2e^- \Leftrightarrow Na_2O$$

Since the anode is sealed from the atmosphere, the equilibrium point of the anode reaction depends only on the O_2 partial pressure in the small volume between the NASICON disc and the aluminium oxide disc. Each reaction gives rise to a particular electron concentration in the corresponding electrode. The charge difference can then be measured as a voltage between the two electrodes. The exact nature of the processes within the sensor cell, and in particular the interactions at the cathode boundary layers, are to a large extent not understood. Empirical research has established, however, that the behaviour of the cell accurately follows the Nernst equation:



$$EMF[mV] = E_C \cdot (R \cdot T)/(2 \cdot F) \cdot \ln[P(CO_2)]$$

where $P(CO_2)$] is the CO_2 partial pressure, E_C is a constant for the cell, R is the ideal gas constant, T is temperature in Kelvin, F is the Faraday constant, and EMF is the electromotive force of the cell.

Since the sensor is designed for use in atmospheric conditions, the dependency of the cathode reaction on the O_2 partial pressure can be neglected, as the O_2 concentration only ever deviates slightly from the value of 21 % by volume. ***Figure A*** *shows the step response of the TGS4160 to changes in gas concentration. The sensor has a linear temperature dependence as shown in* ***Figure B****, which can be taken into account in the signal conditioning circuit with the help of the built-in thermistor.*

TGS4160s have been in continuous testing since 1996. So far no noticeable changes in performance or sensor failures have been observed.

Example circuit

The algorithm described above has been optimised in the light of practical experience and programmed into a microcontroller, which is available as a standard component. **Figure 6** shows the TGS4160 along with the ready-made AM4 module, which includes all the electronics required for a ventilation control system apart from the power driver stage. The sensor has already been successfully used in ventilation control applications, and its suitability for mass production has been demonstrated.

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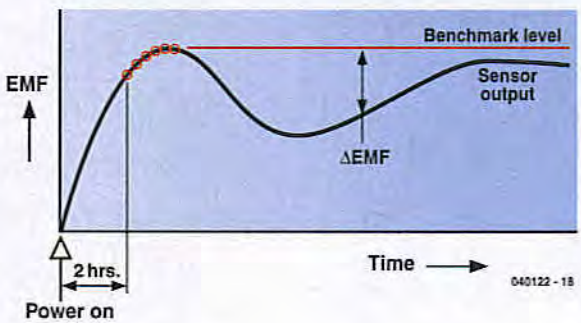

Figure 5. Determining the reference level in software.

Data sheet: www.unitronic.de/CO2
(German website, data sheet in English)

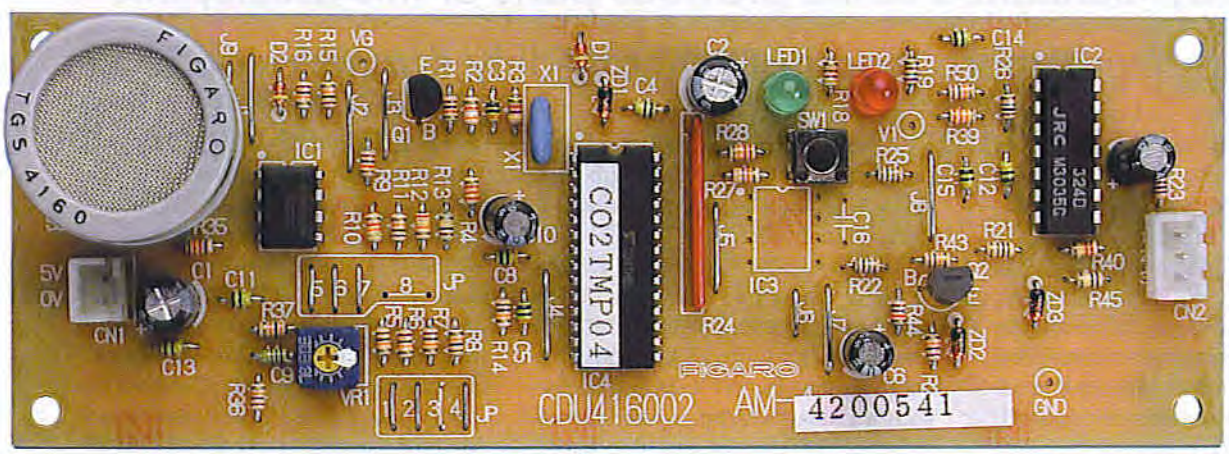

Figure 6. For experimentation and application: the AM4 module.