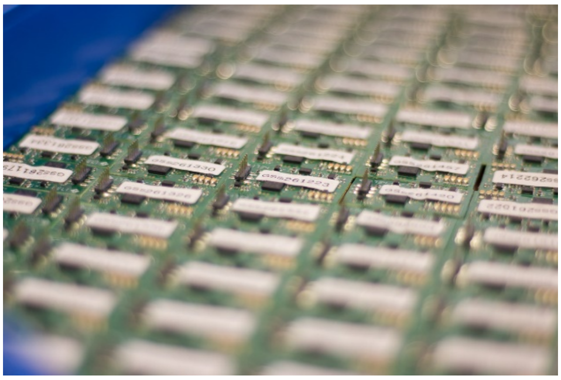
APPLICATION NOTE

AN009: CO_2 Sensors for Ventilator and Capnography Monitoring

ABSTRACT

CO_2 sensors are used in a variety of medical applications, ranging from simple pH sensitive paper for detecting dissolved levels of CO_2 through to ultra high-speed sensors for capnography for helping diagnose heart and lung function. Gas Sensing Solutions (GSS) is a world-leader in designing CO_2 sensors ideal for a range of these medical applications.



A ventilator helps the patient to breathe. An airway is connected to the patient either with a mask or through tubes in the mouth or nose. Ventilators blow air into the lungs replicating the normal breathing. Releasing pressure causes the lungs to relax and exhale naturally. It is possible to synchronise the output from the machine with the patient's own breathing patterns.

When people breathe normally, a tightening of the diaphragm and other muscles inhales air into the lungs. Oxygen then diffuses into the bloodstream through the lung walls. CO_2 is diffused into the lungs from the blood and exhales when the muscles relax.

The level of CO_2 exhaled by the patient is a key indicator their health condition. There is an on-going desire to improve the fidelity of CO_2 measurements to help diagnose patient condition in real time and with greater certainty.

This application note describes some of the sensor attributes and issues that need to be overcome, in order for them to be used in demanding ventilator and capnography equipment.

AN009: CO_2 Sensors for Ventilator and Capnography Monitoring

TABLE OF CONTENTS

AN009: CO_2 Sensors for Ventilator and Capnography Monitoring

INTRODUCTION TO NDIR CO_2 SENSORS

GSS sensors use a technique called non-dispersive infra-red (NDIR). The sensors work by measuring the amount of infra-red light absorbed by the CO_2 gas. The concentration is proportional to the amount of light absorbed as it passes through the gas.

GSS has a long track-record of developing and manufacturing commercially advanced mid-infrared LEDs and photodetectors using its state-of-the-art molecular beam epitaxy (MBE) facility in the UK. The mid infra-red LEDs are tuned to emit a centre wavelength of 4.25um, which is strongly absorbed by the CO_2 gas.

Light emitting diodes (LEDs) and the companion Photodiodes (PDs) detectors are semiconductor devices that are formed by the sequential epitaxy of semiconductor layers onto the surface of a crystal substrate using the MBE machine. LED radiation is generated in the active layer and the emission wavelength of the LED and the spectral response of the PD are determined by the energy gap of the material in the active layers.

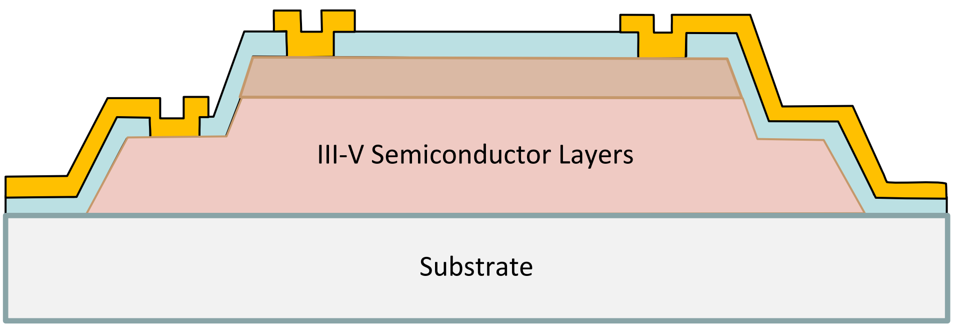


Figure 1: Cross Section of LED Structure

GSS uses a variety of techniques to optimise the semiconductor designs to meet the sometimes market specific requirements of its CO_2 sensors. These semiconductor devices are incorporated into standard sensors or specially configured for demanding customer applications.

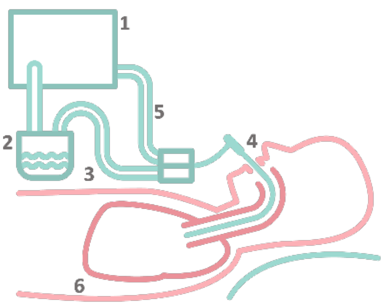
AN009: CO_2 Sensors for Ventilator and Capnography Monitoring

USING CO_2 SENSORS IN MECHANICAL VENTILATORS

The COVID-19 pandemic highlighted the lack of mechanical ventilators for critically ill patients in many countries including advanced economies. At the beginning of the pandemic, many countries ramped up mass-production of ventilators in the belief the health care system would not have enough capacity to cope. However, a poorly considered part of this strategy was the unexpected impact on the ability of hospital infrastructures to be able to fully utilise an increase in the number of ventilators.

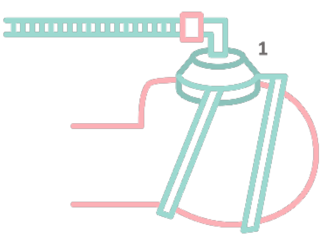
A ventilator is a machine that is designed to deliver air or an air oxygen mixture to a patient that is physically unable to breathe for themselves or requires some help. The gas mixture is pumped into the patient, either directly into the lungs, or via some form of face mask or mouthpiece.

Mechanical Ventilation



1. Ventilator Unit. This contains an air pressure systems and controls.
2. Humidifier. Used to match air to body temperature and adds moisture.
3. Air (Oxygen). Flows to patient.
4. Tube. Inserted into patient's airway.
5. Used Air (Carbon Dioxide). Flows from patient.
6. Lungs.

Non-Invasive Ventilation



1. Face mask is placed over patient's nose and mouth. No tube is inserted into airway.

Figure 2: Ventilator Operation

AN009: CO_2 Sensors for Ventilator and Capnography Monitoring

The gas delivered from a ventilator is a mixture of approximately 21% oxygen, 78% nitrogen, trace amounts of carbon dioxide and the remainder from other inert gases. The air that is exhaled however is different with a composition that depends on the health of the patient. Typically, it is 16% oxygen, 78 % nitrogen, 5% carbon dioxide and about 1% of other gases.

About 5% of the oxygen is exchanged by the patient into carbon dioxide, but the remaining oxygen is exhausted. Most ventilators will exhaust into the atmosphere, with the exhaled oxygen wasted. Whilst this may be deemed acceptable in existing applications, the dramatic increase in the number of ventilators precipitated by the COVID-19 pandemic has highlighted concerns about the ability of the patient care infrastructure hospitals to deliver enough oxygen to the ventilators. Oxygen and other gases are typically piped under pressure around a hospital and delivered to where they are needed. Installation of large numbers of ventilators may put a severe strain on the ability of the care infrastructure to deliver enough oxygen to the point of need.

One way to overcome this potential limitation is to re-cycle the exhausted oxygen instead of venting it into the atmosphere. This so-called closed-loop or closed-circuit system demands two key features. It is critical to ensure all the CO_2 is removed from the exhausted gas. The breathing reflex is triggered by CO_2 concentration levels in the blood and increasing levels can be extremely uncomfortable for the patient. Therefore, exhaled CO_2 must be removed from the air before it can be re-cycled.

To remove CO_2 requires a device called a scrubber. This is a piece of equipment that is designed to absorb CO_2, typically consisting of a material that chemically reacts with the CO_2 in an exothermic reaction. The efficacy of this scrubbing process needs to be measured, both to ensure it is working correctly and to determine when the material needs to be replaced.

GSS has a family of sensors ideally suited to this application. The ExplorIR-W-F is designed to take 2 measurements per second, which supports real time analysis of CO_2 levels in the exhaust gas. The flow port adaptor attached to the main sensor body helps cycle the exhaust gas for rapid measurements.

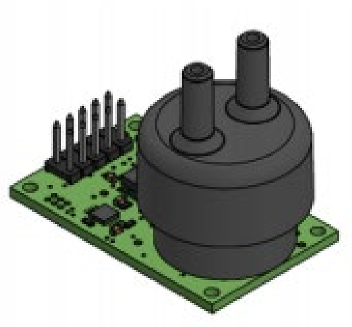


Figure 3: ExporIR-W with Flow Port Adaptor

AN009: CO_2 Sensors for Ventilator and Capnography Monitoring

In addition, the ExplorIR-W also offers a digital alarm that can be used to drive a visual indicator of CO_2 levels. The SprintIR-6S offers similar functionality but with an even faster sampling speed of 20Hz.

PATIENT MONITORING

The operational parameters of the ventilator are set based on several different vital signs gathered by the patient monitoring system. The patient monitor may be integrated into the ventilator or a separate piece of equipment. Parameters includes blood pressure, heart rate (ECG), oxygen saturation and CO_2 levels. CO_2 monitoring during respiration is called capnography and is usually part of the overall patient monitoring system when used in conjunction with a ventilator.

Capnography is used to determine several patient vital signs. CO_2 is a product of the body metabolising carbohydrates, fats, and amino acids, in a process known as cellular respiration. CO_2 is passed from the blood to the lungs in a process called perfusion and expelled through ventilation.

The CO_2 expirated from the body is parameterised in a number of different ways. End-tidal Carbon Dioxide ($ETCO_2$) is the level of Carbon Dioxide that is released at the end of an exhaled breath. Monitoring of the quantity, rate, and shape of the $ETCO_2$ waveform is an invaluable tool for patient monitoring. Analysis of the $ETCO_2$ waveform shape allows you to generate information about the metabolism, ventilation, perfusion and health of the patient. The shape of the waveform should normally be a rectangle with rounded corners. Different waveform shapes can indicate different conditions. This analysis is becoming increasingly sophisticated and is driving the demand for faster and more accurate CO_2 sensing devices.

AN009: CO_2 Sensors for Ventilator and Capnography Monitoring

CAPNOGRAPHY

Capnograph devices generally fall into two categories, either main-stream or side-stream sensing.

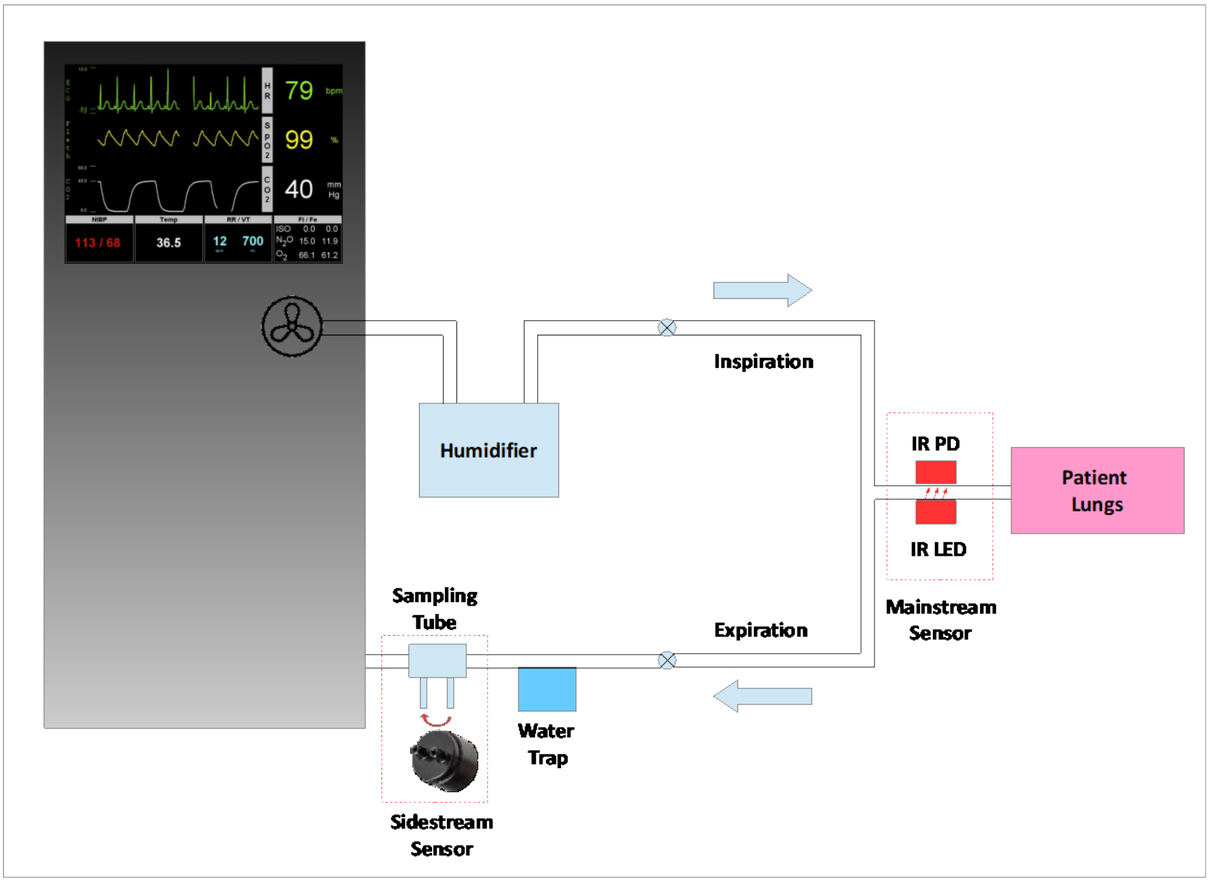


Figure 4: Schematic of Capnography Monitor

AN009: CO_2 Sensors for Ventilator and Capnography Monitoring

SIDE-STREAM SENSING

A side-stream configuration is one where the expirated air from the patient is sampled away from the main flow back to the ventilator. The CO_2 sensor is placed in the sample flow and this placement mitigates some of the application issues that arise when sampling expired air. High humidity can cause condensation without special precautions, and mouth secretions can become a problem if not dealt with correctly. GSS has written an application note on how to mitigate the impact of condensation (AN008-Reducing-the-Impact-of-Condensation-Application-Note-Rev-1.pdf). The other key advantage of a side-stream position is that the sensor does not need to be integrated into the tubing directly attached to the patient, making it easier to accommodate as well as being less sensitive to power consumption and size restrictions.

Whilst side-stream sensing has some advantages, there are several disadvantages. The expired gas has longer to travel, and therefore the response time will be longer. As described earlier, accurate CO_2 morphology needs an understanding of how the signal changes over time and this signature can be 'smeared' when the gas must travel further to reach the sensor. Short term peaks may be partially averaged out due to turbulent flow in the sampling path.

MAIN-STREAM SENSING

In a main-stream capnograph, the expirated breathe is sampled directly in the main airway path. All the same problems of condensation and mouth secretions are present in the main-stream sensing application, but with the added complication of having to mitigate the effects whilst maintaining light weight, low power and small size due to the location close to the patient.

AN009: CO_2 Sensors for Ventilator and Capnography Monitoring

CO_2 SENSOR DESIGN CONSIDERATIONS

GSS has several cost-effective NDIR based gas sensors capable of being used in capnography applications depending on the configuration and positioning of the CO_2 sensor. The ideal sensor will depend to some extent what architecture is being used. In a side stream architecture, the expired gas from the patient is sampled away from the main air flow and is less demanding from a sensor point of view. In a mainstream architecture, the expired gas is measured directly in the main flow and is especially onerous.

Regardless of the architecture, the demands on the sensor depends on what information needs to be acquired. Increasingly, doctors are looking at the detailed morphology of the CO_2 waveforms to help diagnose patient health. To improve the fidelity of the measurements, there are several factors that need to be considered.

Accurate CO_2 morphology requires an in-depth understanding of how the waveform shape evolves over time. The CO_2 waveform must be analysed essentially in real time and with sufficient resolution to identify specific health issue markers. There are several design constraints that must be considered when designing a CO_2 sensor suitable for this requirement.

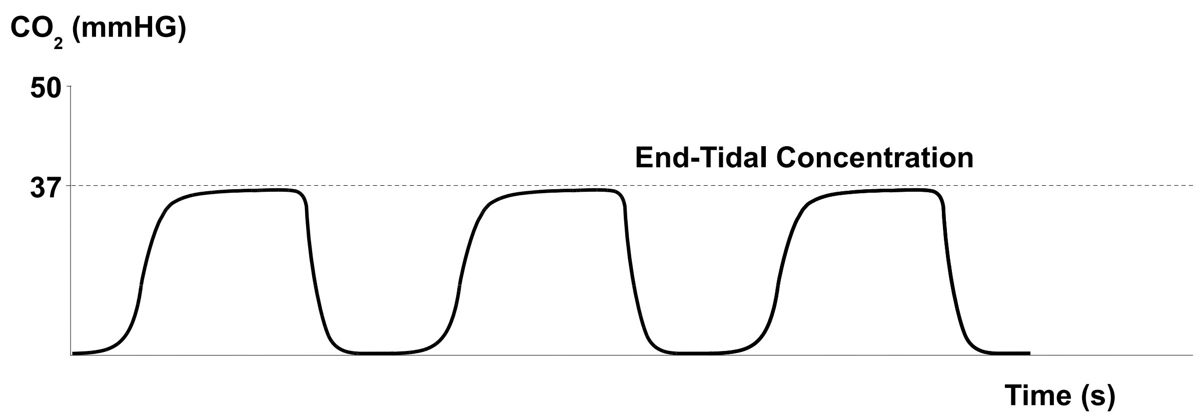


Figure 5: Arterial carbon dioxide pressure ($PaCO_2$) waveform

For historical reasons, CO_2 levels have also been reported as a partial pressure, traditionally measured as the height of a column of mercury in mmHg.

$$CO2\ Concentration\ (\%) = \frac{CO2\ Partial\ Pressure\ (mmHg) * 100}{760}$$

A partial pressure of 37mmHg is approximately 4.9% CO_2.

AN009: CO_2 Sensors for Ventilator and Capnography Monitoring

SENSOR ACQUISITION RATE AND RESOLUTION

A capnograph is a waveform (as above) that represents the varying CO_2 level throughout the breath cycle. The shape of the waveform can change quite dramatically depending on patient condition. Accurately and stable sampling the waveform over time can represent a significant challenge for the CO_2 sensing system.

The number of breaths is normally in the range of 12-20 per minute so the average sampling rate of the system does not need to be very high. Capturing the $ETCO_2$ level as represented by the peak CO_2 in the above waveform is straightforward.

However, as discussed previously, new diagnostic requirements are driving the need for improvements in CO_2 waveform morphology. This means the waveform must be captured in near real time, and at high precision. In order to achieve this, a number of obstacles need to be overcome.

For the sensor to perform correctly, the gas that has been measured has to be removed from the system before the new gas can be sampled. In most side-stream applications, the expired gas is pumped into the sensing system and it is helpful to minimise the overall gas volume in the sensor and connecting pipes. GSS sensors are designed to have a small gas measurement chamber, which only requires approximately 2.8ml of gas for a single measurement.

The sensor sampling rate is an essential component in ensuring the waveform is captured with high fidelity. In addition to the basic amplitude of the waveform, the spatial frequency content is critical in providing more accurate waveform morphology. Harry Nyquist was helpful in defining the Nyquist Sampling Theorem. It states that a band-limited continuous-time signal can be sampled and perfectly reconstructed from its samples if the waveform is sampled over twice as fast as the highest frequency component.

GSS has two sensors that are specifically designed for high-speed sampling of CO_2 gas. The SprintIR-6S samples at 20Hz and the SprintIR-R at 50Hz. This means that in the case of the SprintIR-R, and assuming the gas flow rate can support it, the sensor can resolve spatial frequency components of up to 25Hz at 12-bit resolution. This makes it ideal to support a new generation of capnography monitoring applications.

AN009: CO_2 Sensors for Ventilator and Capnography Monitoring

DIGITAL FILTERING

The signal from the LED is detected by the photo-diode within the sensor. This signal is intrinsically noisy and is typically filtered by the sensor before it is read out by the user. However, time dependent indicators in the CO_2 waveform can be corrupted or removed entirely by this digital filtering process.

For most CO_2 sensing applications, the time domain signature is not that important, and the user is generally only concerned with the slow evolution of concentration levels over extended periods of time. Note that the sampling speed is not the same as responsiveness. There are many applications where the CO_2 sensor must be able to respond very rapidly to the change in concentration but where the time domain signature is not critical.

However, accurate CO_2 morphology for patient diagnostics is entirely dependent on both the fidelity of the waveform in time as well as in amplitude. All GSS sensors have the ability to output unfiltered data. This allows the user to deploy sophisticated digital filtering techniques without the need to compromise responsiveness, sampling speed or signal fidelity.

CONCLUSION

GSS offers a number of technologies that are well matched to the emerging requirements of next generation CO_2 monitoring applications. Its range of SprintIR sensors are low power, compact and compatible with pumped gas analysis systems. Combined with their accurate, high speed and resolution sampling features, they provide the user with the ability to analyse the CO_2 waveform with unmatched fidelity.

AN009: CO_2 Sensors for Ventilator and Capnography Monitoring

AN009: CO_2 Sensors for Ventilator and Capnography Monitoring

ADDRESS

Gas Sensing Solutions Ltd.
Grayshill Road
Cumbernauld
G68 9HQ
United Kingdom

AN009: CO_2 Sensors for Ventilator and Capnography Monitoring

REVISION HISTORY

DATE	RELEASE	DESCRIPTION OF CHANGES	PAGES
08/10/2020	1.0	First revision	All