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Handheld Gas Sensing Module for Future Integration into Easy-to-Use Instruments in Environmental Sensing Applications – Status and Outlook

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Summary:
The current development focuses on a gas sensing unit based on a modular design, which has the potential to be used in future devices for detecting harmful volatile organic compounds (VOCs) in the environment. It is based on ion mobility spectrometry (IMS) that is a highly sensitive and selective method for the detection of even low concentrations of substances in air. The core component of the developed module is a miniaturized chip device that integrates the ion filter and detector. These components form the IMS module, which can be easily integrated into new innovative systems.

Keywords: ion mobility spectrometry, environmental sensor, handheld, sensing module, VOC

Introduction

There is a need for easy-to-use and portable devices that enables the identification of analytes in the environment. Gaseous substances that belong to the group of volatile organic compounds (VOCs) are well known and are often harmful even in low ppb concentrations [1, 2]. These must be reliably detected, for example, in applications such as on-site emission control.

The state-of-the-art currently uses laboratory methods that can detect very low concentrated substances from a complex gas mixture. Gas chromatography coupled with mass spectrometry (GC-MS) is a common example method. The disadvantage of this method is that the samples must first be transferred to the laboratory and analyzed there. This is a time-consuming process that requires the expertise of qualified specialists. This is not convenient for fast and frequent on-site measurements. The intended application scenario therefore requires portable and easy-to-use analyzing systems that can be used in different locations. The development of such analytical instrumentation needs appropriate sensor components and integration technologies. The current work focusses on both aspects. The overall aim is to develop a modular component that can be used for further product development with relatively little effort.

Ion Mobility Spectrometry

The sensor component determines both the applicability as well as the effort required for system integration and automated data analysis. With focus on the sensor technology, ion mobility spectrometry (IMS) is a very promising approach for such a development. IMS enables the detection of low concentrated substances in the lower ppb-range under ambient conditions [1-3]. Moreover, IMS can detect single substances of a gas mixture. An ionization source generates the analyte ions, e.g. by using a UV discharge lamp. Electrical fields are used in the ion filter to separate ion species according to their specific ion mobility, K. The mean drift velocity, v, the electrical field strength, E, and ion mobility, K, are related as follows:

$$v = E\,K. \qquad (1)$$

The ions passing the filter then are captured in the detector.

A time-of-flight ion filter is a common implementation for IMS, where ions are traveling along a given drift length under a constant electric field. The drift time depends on the ion specific mobility, K, and can be used to distinguish different ion species. This so-called drift tube or drift time IMS (DTIMS) is a convenient implementation into laboratory equipment. A miniaturization for a use in handheld systems and an appropriate manufacturing technology for a production of application-relevant quantities is not feasible.

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Chip-based Ion Mobility Spectrometry

With regard towards miniaturization, other filter principles have to be implemented. Differential ion mobility spectrometry (DMS) or high-field asymmetric waveform ion mobility spectrometry (FAIMS) is a promising filter setup for IMS. DMS/FAIMS uses high electrical field strengths that have an impact on the ion mobility, K(E). This change of the mobility is ion specific and is based on ion cluster reactions that occur under ambient conditions. The basic setup of DMS can be found in Fig. 1. Special shaped voltage signals are applied to the filter electrodes and lead to different electrical field strength conditions in the ion filter. Only ion species with a suitable K(E)-characteristic reach the detector. All other ions move towards one of the filter electrodes. The ions get neutralized when they collide with the filter electrodes. A DC compensation voltage adjusts the filter behavior. A sweep of the compensation voltage leads to the characteristic DMS spectrum. A summary of the main basics and typical applications can be found in [1], [2] and [4].

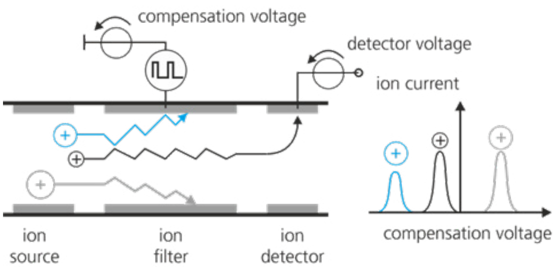

Fig. 1. Electrode configuration and typical ion trajectories for differential ion mobility spectrometry (DMS)/high-field asymmetric waveform ion mobility spectrometry (FAIMS) (from [5]).

A parallel electrode configuration for the ion filter presents one promising opportunity for DMS. A small electrode gap is favorable to generate high electrical field strengths with moderate voltage levels. The use of silicon-based microfabrication technologies allows the implementation of electrode gaps in the µm-scale with high accuracy. Throughout the last years, a chip-based device was developed by [5] and [6]. A DMS-based ion filter and ion detector is implemented in one chip device. Deep reactive ion etching (DRIE) is used to generate electrode structures and electrode gaps. DRIE is one method to generate trenches with a high aspect ratio (trench depth – trench width) in silicon wafers and is very common for the manufacturing of micro-electromechanical systems (MEMS). This is a very important step in the overall wafer processing sequence. Fig. 2 shows typical structures and the high accuracy.

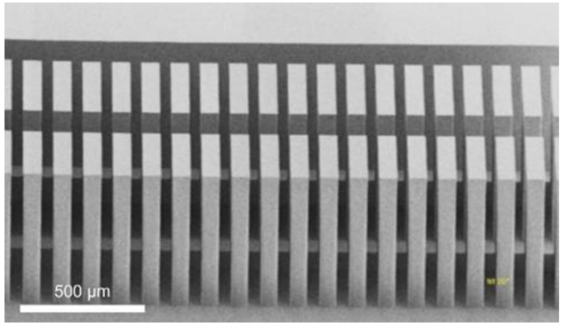

Fig. 2. Developed chip device with detailed view of the etched structures that build the integrated ion filter and ion detector (from [5]).

Measurements and the Gas Sensing Module

For a proof of function and for a later development of an IMS instrumentation, other functional components have to be integrated next to the IMS chip device. This involves the ion source, gas connectors, electronic boards to drive the ion filter, the amplification of the current signal at the detector and the control of the overall system functionality.

A setup for use in a laboratory environment was developed. The schematic setup is shown in Fig. 3. This was the first step with focus on the principal proof of function. Results can be found in [6,7] and show the expected DMS spectra (Fig. 4). The measurements were previously carried out with single substance mixtures. This means that a specific analyte such as acetone was added to a carrier gas (N2) and transferred to the demonstrator. In further measurements, a different analyte like pentanone was added to the carrier gas. The results were evaluated in terms of their distinguishability. Specifically, a different position of the peak maximum in relation to the compensation voltage is expected. For typical ketones, which belong to the group of VOCs, differences could be determined.

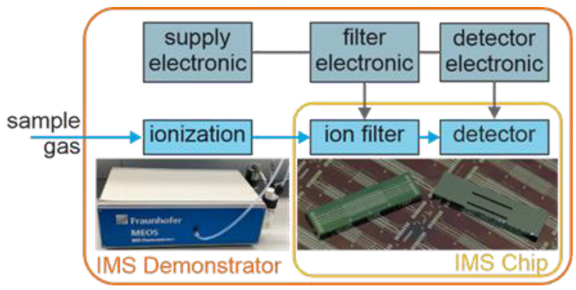

Fig. 3. Developed chip device with integrated ion filter and ion detector (from [6]).

For the next step, the development focused on the system components that are necessary to use the IMS chip with the integrated ion filter and detector.

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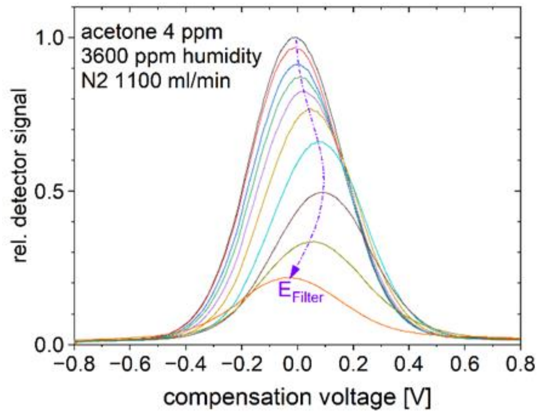

Fig. 4. Measured spectra for acetone in nitrogen (N2) that shows the typical DMS behavior. The shift of the peak maximum at different filter field strengths (E_{Filter}) depends on the analyte and can be used to distinguish them (from [6]).

Due to its unique design and specific gas supply requirements, the chip presents challenges for a direct transfer in terms of product development. Furthermore, the electronics have very specific requirements and other components such as the ionization source must form a combined unit with the chip device. The gas sensing modules should reduce these hurdles. The aim of the current concept is to integrate the IMS chip, the ionization source and the boards with electronics from an early development stage into one component. The results are shown in Fig. 5. This module contains the following parts:

- IMS chip with integrated ion filter and ion detector
- UV gas discharge lamp for ionization (atmospheric pressure photoionization)
- PCB boards for:
  * interface board IMS chip – electronics
  * filter driver
  * interface board: IMS chip – amplifier

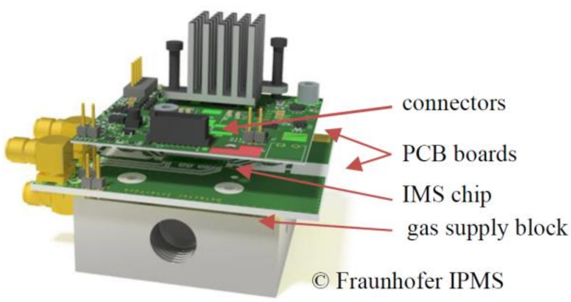

Fig. 5. First version of a handheld gas sensing module. This module includes the IMS chip, the connections for the gas supply and the gas supply block. The UV discharge lamp as an ionization source is located on the backside (not shown) with the primary electronic boards for the generation of the filter voltage. The electrical connections for the filter electronics and the detector with secondary electronics and power supply are also shown.

The developed gas sensing module is a possibility for an integration into new systems. The development effort is therefore much lower. Some components, like driver electronics for the discharge lamp and the overall power supply are currently placed on separate boards. Their integration will be part of research and development projects in near future.

Summary and Outlook

An adaptive gas sensing module is developed that allows a prospective use in environmental analysis, e.g., for the detection of harmful VOCs in low ppb concentrations. A previously developed IMS chip is the key element of this module. Other essential parts like the ionization source and the filter driver board are included in the module setup. This allows a possible future integration into handheld and portable measurement systems. Results from the IMS chip show the basic proof of function for typical analytes.

Ongoing developments are currently focused on improving the performance of the IMS chip and integrating other required system components. After this upcoming phase, a module will be available that can be used as a promising and important part of new product developments. This enables access to new markets like environmental sensing

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