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CHEMICAL SENSORS DEFINITIONS AND CLASSIFICATION

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Chemical sensors: definitions and classification

DEFINITIONS

A chemical sensor is a device that transforms chemical information, ranging from the concentration of a specific sample component to total composition analysis, into an analytically useful signal. The chemical information, mentioned above, may originate from a chemical reaction of the analyte or from a physical property of the system investigated.

A physical sensor is a device that provides information about a physical property of the system.

A chemical sensor is an essential component of an *analyzer*. In addition to the sensor, the analyzer may contain devices that perform the following functions: sampling, sample transport, signal processing, data processing. An analyzer may be an essential part of an automated system. The analyzer working according to a sampling plan as a function of time acts as a monitor.

Chemical sensors contain two basic functional units: a receptor part and a transducer part. Some sensors may include a separator which is, for example, a membrane.

In the *receptor* part of a sensor the chemical information is transformed into a form of energy which may be measured by the transducer.

The *transducer* part is a device capable of transforming the energy carrying the chemical information about the sample into a useful analytical signal. The transducer as such does not show selectivity.

The receptor part of chemical sensors may be based upon various principles:

- physical, where no chemical reaction takes place. Typical examples are those based upon measurement of absorbance, refractive index, conductivity, temperature or mass change.
- chemical, in which a chemical reaction with participation of the analyte gives rise to the analytical signal.
- biochemical, in which a biochemical process is the source of the analytical signal. Typical examples are microbial potentiometric sensors or immunosensors. They may be regarded as a subgroup of the chemical ones. Such sensors are called *biosensors*.

In some cases it is not possible to decide unequivocally whether a sensor operates on a chemical or on a physical principle. This is, for example, the case when the signal is due to an adsorption process.

Sensors are normally designed to operate under well defined conditions for specified analytes in certain sample types. Therefore, it is not always necessary that a sensor responds specifically to a certain analyte. Under carefully controlled operating conditions, the analyte signal may be independent of other sample components, thus allowing the determination of the analyte without any major preliminary treatment of the sample. Otherwise unspecific but satisfactory reproducible sensors can be used in series for multicomponent analysis using a multivariate calibration software and signal processing. Such systems for multicomponent analysis are called sensor arrays.

CLASSIFICATION OF SENSORS

The development of instrumentation, microelectronics and computers makes it possible to design sensors utilizing most of the known chemical, physical and biological principles that have been used in chemistry.

Chemical sensors may be classified according to the operating principle of the transducer.

1. *Optical* devices transform changes of optical phenomena, which are the result of an interaction of the analyte with the receptor part. This group may be further subdivided according to the type of optical properties which have been applied in chemical sensors:

a) absorbance, measured in a transparent medium, caused by the absorptivity of the analyte itself or by a reaction with some suitable indicator.

b) reflectance is measured in non-transparent media, usually using an immobilized indicator.

c) luminescence, based on the measurement of the intensity of light emitted by a chemical reaction in the receptor system.

- d) fluorescence, measured as the positive emission effect caused by irradiation. Also, selective quenching of fluorescence may be the basis of such devices.
- e) refractive index, measured as the result of a change in solution composition. This may include also a surface plasmon resonance effect.
- f) optothermal effect, based on a measurement of the thermal effect caused by light absorption.
- g) light scattering, based on effects caused by particles of definite size present in the sample.

The application of many of these phenomena in sensors became possible because of the use of optical fibres in various configurations. Such devices have also been called optodes. It should be emphasized that fibre optics now commonly used are only technical devices applicable in a large group of optical sensors which can be based on various principles.

2. *Electrochemical* devices transform the effect of the electrochemical interaction analyte – electrode into a useful signal. Such effects may be stimulated electrically or may result in a spontaneous interaction at the zero-current condition. The following subgroups may be distinguished:

- a) voltammetric sensors, including amperometric devices, in which current is measured in the d.c. or a.c. mode. This subgroup may include sensors based on chemically inert electrodes, chemically active electrodes and modified electrodes. In this group are included sensors with and without (galvanic sensors) external current source.
- b) potentiometric sensors, in which the potential of the indicator electrode (ion-selective electrode, redox electrode, metal/metal oxide electrode) is measured against a reference electrode.
- c) chemically sensitized field effect transistor (CHEMFET) in which the effect of the interaction between the analyte and the active coating is transformed into a change of the source-drain current. The interactions between the analyte and the coating are, from the chemical point of view, similar to those found in potentiometric ion-selective sensors.
- d) potentiometric solid electrolyte gas sensors, differing from class 2b) because they work in high temperature solid electrolytes and are usually applied for gas sensing measurements.

3. *Electrical* devices based on measurements, where no electrochemical processes take place, but the signal arises from the change of electrical properties caused by the interaction of the analyte.

- a) metal oxide semiconductor sensors used principally as gas phase detectors, based on reversible redox processes of analyte gas components.
- b) organic semiconductor sensors, based on the formation of charge transfer complexes, which modify the charge carrier density.
- c) electrolytic conductivity sensors.
- d) electric permittivity sensors.

4. *Mass sensitive* devices transform the mass change at a specially modified surface into a change of a property of the support material. The mass change is caused by accumulation of the analyte.

- a) piezoelectric devices used mainly in gaseous phase, but also in solutions, are based on the measurement the frequency change of the quartz oscillator plate caused by adsorption of a mass of the analyte at the oscillator.
- b) surface acoustic wave devices depend on the modification of the propagation velocity of a generated acoustical wave affected by the deposition of a definite mass of the analyte.

5. *Magnetic* devices based on the change of paramagnetic properties of a gas being analysed. These are represented by certain types of oxygen monitors.

6. *Thermometric* devices based on the measurement of the heat effects of a specific chemical reaction or adsorption which involve the analyte. In this group the heat effects may be measured in various ways, for example in the so called catalytic sensors the heat of a combustion reaction or an enzymatic reaction is measured by use of a thermistor. The devices based on measuring optothermal effects (1f) can alternatively be included in this group.

7. Other physical properties as for example X-, β - or Γ - radiation may form the basis for a chemical sensor in case they are used for determination of chemical composition.

This classification represents one of the possible alternatives. Sensors have, for example, been classified not according to the primary effect but to the method used for measuring the effect. As an example can be given the so-called catalytic devices in which the heat effect evolved in the primary process is measured by the change in the conductivity of a thermistor. Also, the electrical devices are often put into one category together with the electrochemical devices.

Sensors have also been classified according to the application to detect or determine a given analyte. Examples are sensors for pH, for metal ions or for determining oxygen or other gases.

Another basis for the classification of chemical sensors may be according to the mode of application, for example sensors intended for use in vivo, or sensors for process monitoring and so on.

It is, of course, possible to use various classifications as long as they are based on clearly defined and logically arranged principles.

The biosensors are not presented as a special class because the process on which they are based is, in general, common to chemical sensors. They may be also differentiated according to the biological elements used in the receptor. Those may be: organisms, tissues, cells, organelles, membranes, enzymes, antibodies, etc. The biosensors may have several enzymatic systems coupled which serve for amplification of the signal.

Various sensors may be combined in sets which are often called multisensors.

GENERAL REFERENCES

1. Proceedings of the International Meeting on Chemical Sensors, Fukuoka, Japan, September 19-22, 1983, Editors: T. Seyma, K. Fueki, J. Shiokawa and S. Suzuki, Elsevier-Kodansha, Amsterdam and Tokyo, 1983.
2. H. Wohltjen, Chemical Microsensors and Microinstrumentation, *Anal. Chem.*, **56**, 87A, 1984.
3. W.R. Seitz, Chemical Sensors Based on Immobilized Indicators and Fibre Optics, *CRC Critical Reviews in Anal. Chem.*, **19**, 135, 1988.
4. M. Thompson and U. J. Krull, Biosensors and Bioprobes, *Trends in Anal. Chem.*, **3**, 173, 1984.
5. T.E. Edmonds (ed.), *Chemical Sensors*, Blackie and Sons Ltd., London, 1988.
6. A.P.F. Turner, I. Karube and G.S. Wilson (eds.), *Biosensors. Fundamentals and Applications*, Oxford University Press, New York, 1987.
7. R. Niessner, *Chemische Sensoren: Prinzipien und Anwendungen in Analytiker Taschenbuch*, vol. 7. (eds.: W. Fresenius et. al.) Springer Verlag, Berlin, 1988, p. 55.
8. D. Schuetzle, R. Hammerle and J. Butler (eds.), *Fundamentals and Applications of Chemical Sensors*, ACS Symposium Series, 309 American Chemical Society, 1986.
9. W. Gopel, Entwicklung Chemischer Sensoren. Empirische Kunst oder systematische Forschung? *Techn. Messen*, **52**, 47, 92, 175, 1985.
10. C. Nylander, Chemical Sensors and Biological Sensors, *J. Phys. Sci. Instr.*, **18**, 736, 1985.
11. J. Janata and A. Bezech, Chemical sensors, *Anal. Chem.*, **60**, 62R, 1988.
12. J. Janata, R.J. Huber (eds.), *Solid-State Chemical Sensors*, Academic Press, New York, 1985.
13. S. Middelhoek, Ed., *Sensors and Actuators*, vol. 10, 1986.
14. F. Scheller, F. Schubert, D. Pfeiffer, R. Hintsche, I. Dransfeld, R. Renneberg, U. Wollenberger, K. Riedel, M. Pavlova, M. Kuhn, H-G. Muller, P.M. Tan, W. Hoffmann and W. Moritz, Research and development of biosensors, *Analyst*, **114**, 653, 1989.
15. M.A. Arnold and M.E. Meyerhoff, Recent advances in the development and analytical applications of biosensing probes, *CRC Critical Reviews in Anal. Chem.*, **20**, 149, 1988.