An Artificial Nose Based on Microcantilever Array Sensors

H P Lang[1], J P Ramseyer, W Grange, T Braun, D Schmid, P Hunziker, C Jung, M Hegner, C Gerber

National Center of Competence in Research for Nanoscale Science, Institute of Physics of the University of Basel, Klingelbergstrasse 82, CH-4056 Basel, Switzerland

E-mail: Hans-Peter.Lang@unibas.ch

Abstract. We used microfabricated cantilever array sensors for an artificial nose setup. Each cantilever is coated on its top surface with a polymer layer. Volatile gaseous analytes are detected by tracking the diffusion process of the molecules into the polymer layers, resulting in swelling of the polymer layers and therewith bending of the cantilevers. From the bending pattern of all cantilevers in the array, a characteristic 'fingerprint' of the analyte is obtained, which is evaluated using principal component analysis. In a flow of dry nitrogen gas, the bending of the cantilevers is reverted to its initial state before exposure to the analyte, which allows reversible and reproducible operation of the sensor. We show examples of detection of solvents, perfume essences and beverage flavors. In a medical application, the setup provides indication of presence of diseases in patient's breath samples.

1. Introduction

Microfabricated cantilever arrays are derived from atomic force microscopy (AFM) cantilevers. We demonstrate their use as chemical sensors for volatile analytes [1]. In contrast to AFM no sharp tip or sample surface is needed, because the chemical process to be detected takes place on the cantilever surface. For this purpose, the upper cantilever surface is either functionalized to enable chemical reactions or passivated to prevent those reactions. The functional layer is either highly specific to the target molecule, i.e. by chemical key-lock interactions, or rather partially specific, e.g. by coating the cantilever surface with polymers that allow diffusion of target molecules into the polymer layer at different rates. In the first case the cantilever response is specific mechanical bending of the individual cantilever due to adsorption of molecules resulting in change of surface stress, whereas in the second case the response is the bending pattern of all cantilevers. Each polymer layer interacts in a characteristic way by swelling when exposed to gaseous volatile analytes, producing bending of the cantilever due to expansion of the polymer layer. The process is reversible, as the cantilever array is cleaned in a flow of dry nitrogen, allowing the target molecules to diffuse out of the polymer again until the cantilever deflections reach their initial value.

The major advantages of microcantilever array sensors are their small size, high sensitivity and fast response time [2], as well as their broad range of applicability as the functional coating can be selected according to the desired application, e.g. for chemistry, food and fragrance industries, for quality and authenticity assessment and to establish a reproducible quality level in different production batches.

---

[1] To whom any correspondence should be addressed.

The partial specificity of the functional coating towards volatile organic compounds (VOCs) such as solvents, fragrance and nutrition-related compounds allows characterization of VOCs by evaluating the entire pattern of bending responses from the eight cantilevers. Using the method of principal component analysis (PCA), the individual compounds can be distinguished as clusters of points in the PCA plot, each point representing a measurement. In such an artificial nose [3], cantilever array sensors can rapidly recognize previously measured analytes, but cannot analyze the chemical composition of an analyte, due to the partial specificity of cantilever coatings. The key features of an artificial nose are (i) chemical sensors composed of a physical transducer and a chemical interface layer or a receptor domain with partial specificity; (ii) an appropriate pattern-recognition system to recognize simple or complex odors (pattern classifier), and (iii) a sampling system to reproducibly perform measurements [3]. The sensor array is exposed to the same sample, and produces individual responses as well as a pattern of responses. An artificial nose gives reproducible results, does not wear out, and can be placed in environments that are harmful to human beings.

The magnitude of cantilever deflection is roughly proportional to the concentration of the analyte present. For analyte concentrations of 500ppm, a deflection of several micrometers is observed [4], implying that the current detection limit is in the upper ppb range.

2. Experimental

A microcantilever sensor array (figure 1a) with eight differently coated cantilevers is employed as an "artificial nose" to characterize vapors. The polymer layers were applied by inkjet spotting [5]. It is placed in a measurement chamber, equipped with optical beam deflection readout for each cantilever as well as with inlet and outlet ports for gas streams (figure 1b). An array of eight vertical cavity surface emitting lasers (VCSELs) and a position sensitive detector (PSD) are used for optical beam deflection measurement of the bending of each cantilever separately in a time-multiplexed way. Analytes are carried in a stream of dry nitrogen gas from the headspace above a liquid sample (0.1 ml) in a vial to the measurement chamber using flow controllers (flow rate: 20 ml/min).
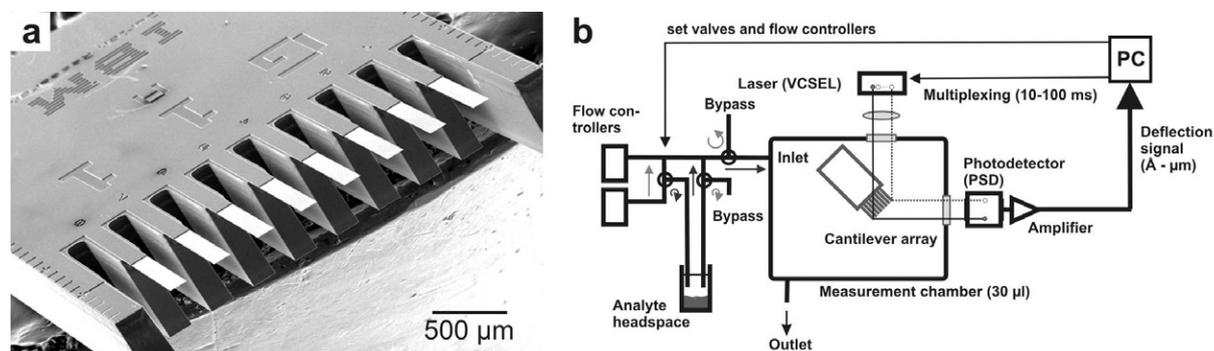
Figure 1: (a) Scanning electron microscopy picture of a microfabricated cantilever sensor array. (b) Schematic of the gas phase cantilever sensor array setup.

3. Results and Discussion

3.1. Solvent detection

Reliable detection of solvent vapors is important in chemical process technology, e.g. for safe handling during storage and transport of large amounts of solvents in containers. In a fast test it can be verified that actually the solvent is in the container that is supposed to be in there. In a laboratory test, 0.1 ml of various solvents was placed in vials, and the vapor from the headspace above the liquid was sampled using the cantilever array artificial nose. Detection of vapors takes place via diffusion of the vapor molecules into the polymer, resulting in a swelling of the polymer and bending of the cantilever. The bending is specific to the interaction between solvent vapor and polymer with respect to time- and

magnitude evolution [2]. Cantilever deflection traces upon injection of dichloromethane vapor at 50s for 10s are shown in figure 2a (Data by Marko Baller). The following polymers were used: 1=PVP, 2=PVP/PU/PS/PMMA, 3=PU/PS/ PMMA, 4=PU/PS, 5=PU, 6=PS/ PMMA, 7=PS, 8=PMMA.

The cantilever deflections at the time points t_1 to t_5 describe the time-development of the curves in a reduced data set, i.e. 8 x 5 = 40 cantilever deflection amplitudes ('fingerprint') that account for a measurement data set. This data set is then evaluated using PCA techniques, extracting the most dominant deviations in the responses for the various sample vapors. The axes refer to projections of the multidimensional datasets into two dimensions (principal components).
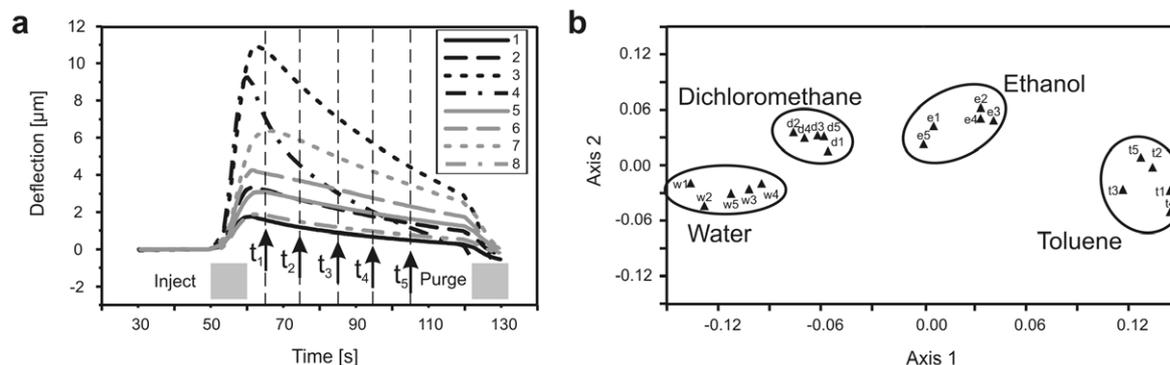

Figure 2: (a) Cantilever deflection traces during exposure of a polymer-coated cantilever array to dichloromethane vapor. (b) PCA plot demonstrating the recognition capability of the cantilever-array based artificial nose.

The labels in the PCA plot (figure 2b) indicate the individual measurements. Vapor injections involved water, ethanol, dichloromethane and toluene. The PCA plot shows well separated clusters of measurements indicating clear identification of vapor samples.

3.2. Fragrance Characterization

Specially trained personnel are employed in fragrance industry to ascertain the quality and authenticity of perfumes by smelling the odor of the chemicals mixed in a well-defined ratio. Such work requires skills, experience and can only be done for a couple of hours in a day. The cantilever-array based artificial nose can be applied 24 h a day without fatigue effects.

Our laboratory test involved perfume essence samples (lemon, wood, flower, musky, oriental; main components: ethanol 35%, water 14%, dipropylene glycol 50%, fragrances <1%) in a stream of dry nitrogen. Figure 3 shows PCA plots demonstrating that the cantilever-array based artificial nose is able to distinguish among the various perfume essences.
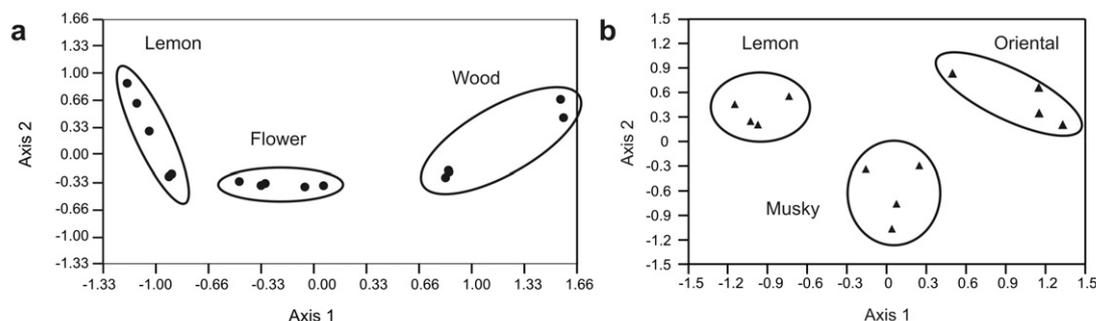
Figure 3: (a) PCA plot of lemon, flower and wood perfume essences. (b) PCA plot of lemon, musky and oriental perfume essences.

3.3. Artificial peach flavors

In food and beverage industry, complex mixtures of a large number of chemical components are used for flavoring products. Peach flavor, for example, is a complex mixture of more than 80 individual constituents. Variation of chemical composition gives the test person still an impression of peachy flavor without being able to tell quantitative differences. To investigate this field of application using our cantilever-array based artificial nose, we exposed the polymer-coated cantilever array to 13 different flavors of peach (sample: headspace above 0.1 ml of peach flavor samples; main component: ethanol >99%, up to 84 individual flavor components: typically <0.1%; in a stream of dry nitrogen).
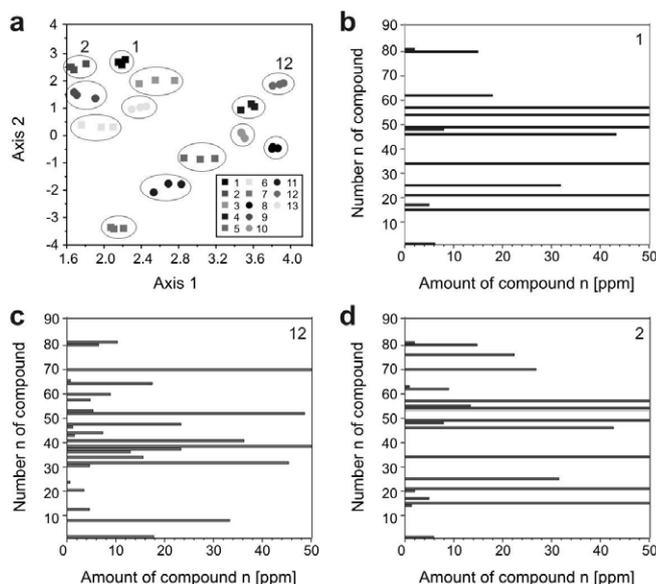
Figure 4: (a) PCA plot of 13 different peach flavors. (b-d) compositional charts of peach flavors 1, 12 and 2. 1 and 2 have similar composition, whereas flavor 12 contains a few ppm of chemical compounds 30 to 40. The exact chemical composition is not disclosed due to trade secrets.

Each of the artificial peach flavor samples was measured 3 times using the cantilever sensor setup. PCA data evaluation is targeted at maximum distinction performance between analytes, i.e., several measurements of the same analyte should yield a cluster in principal-component space, whereas measurements of differing analytes should produce well-separated clusters of measurements. The compositional charts show that the cantilever-array based nose can distinguish between different peach flavor mixtures with distinction sensitivity better than 30 ppm. Figure 4 shows that peach flavors 1 and 2, which were found to be similar in the PCA plot, actually have similar composition, whereas flavor 12 has a different composition. The difference between flavor 1 and 12 lies in additional components present at the 30 ppm level.

3.4. Breath sample characterization as possible indication for diseases

Before using modern diagnosis tools medical doctors examined patient's breath to detect diseases, as certain diseases can be recognized by study of exhaled air. Examples of such findings are: (i) *diabetes mellitus (type II diabetes)*, a severe, chronic form of diabetes caused by insufficient production of insulin and resulting in abnormal metabolism of carbohydrates, fats, and proteins. This disease involves acetone to be present in patient's breath. (ii) *uraemia*, a toxic condition resulting from kidney disease in which there is retention of waste products in the bloodstream normally excreted in the urine. A compound found in patient's breath associated with uraemia is dimethylamine.

Breath samples of two patients suffering from *diabetes mellitus* and *uraemia* were taken and stored in medical plastic bags for exhaled air samples. For comparison, also breath samples from healthy

persons were investigated for reference. For each measurement, 10 ml of exhaled air was removed from the medical plastic bag under temperature-controlled conditions, and injected into the measurement chamber. The cantilever deflections were found to be very reproducible for samples from the same patient, but dissimilar for samples from patients with different diseases (figure 5a-d). The PCA plot shows clear clustering of breath measurements of healthy patients and of patients with acetone breath (diabetes) and uraemia (figure 5e). The cantilever technique allows fast and non-invasive detection of diseases in patient's breath samples.
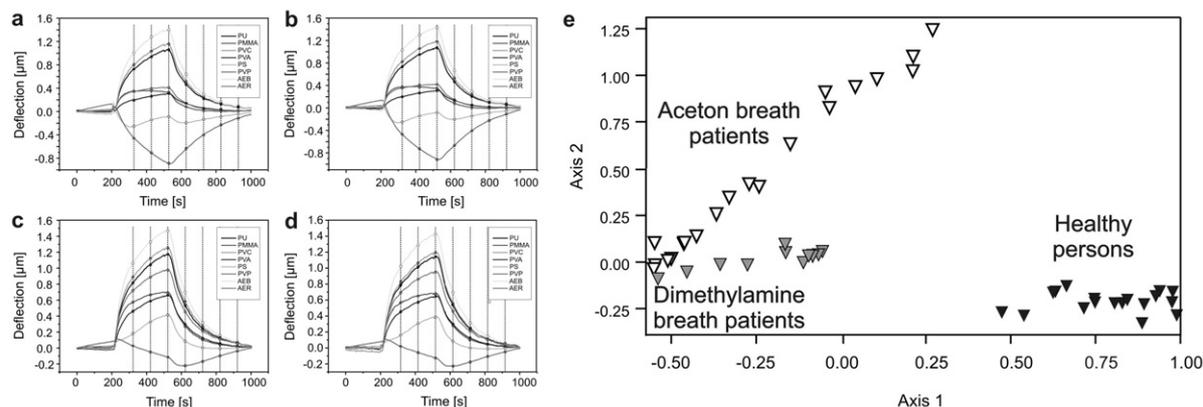
Figure 5: (a)-(b) Cantilever deflection traces acquired during injection of a breath sample of a healthy person, (c)-(d) *ditto*, but for a patient suffering from *uraemia*. (e) PCA plot.

4. Conclusion and Outlook
Our cantilever-array based artificial nose proved successful application in the fields of chemical solvent detection, perfume and beverage flavor characterization, as well as in medicine. As the polymer layer chemistry determines the application, many more utilization areas are foreseeable.

5. Acknowledgements

References
[1] Lang H P, Baller M K, Berger R, Gerber C, Gimzewski J K, Battiston F M, Fornaro P, Ramseyer J P, Meyer E, Güntherodt H J 1999 An artificial nose based on a micromechanical cantilever array *Anal. Chim. Acta* **393** 59-65
[2] Berger R, Gerber C, Lang H P, Gimzewski J K 1997 Micromechanics: a toolbox for femtoscale science: towards a laboratory on a tip *Microelectron. Eng.* **35** 373-379
[3] Gardner J W, Bartlett P N 1992 *Sensors and sensory systems for an electronic nose* (Dordrecht: Kluwer Academic Publishers)
[4] Baller M K, Lang H P, Fritz J, Gerber C, Gimzewski J K, Drechsler U, Rothuizen H, Despont M, Vettiger P, Battiston F M, Ramseyer J P, Fornaro P, Meyer E, Güntherodt H J 2000 A Cantilever Array Based Artificial Nose *Ultramicroscopy* **82** 1-9
[5] Bietsch A, Zhang J, Hegner M, Lang H P, Gerber C 2004 Rapid Functionalization of Cantilever Array Sensors by Inkjet Printing *Nanotechnol.* **15** 873-880