RZ 2985 (# 93031) 12/22/97
Physical Sciences 15 pages

Research Report

Micromechanical Cantilevers: Sensors for Femtoscale Science

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Abstract

The invention of the scanning force microscope linked the use of micromechanics and microscopy at the atomic scale. The extreme sensitivity of micromechanical devices combined with nanoscale science techniques extends their use well beyond imaging surface properties. For ultraprecise measurements, micromechanical devices are potentially very promising because a variety of chemical and physical effects can be transduced into a mechanical response on the nanometer scale. Cantilever-based sensors, used in configurations to detect **mass**, **heat**, and **stress**, allow the analysis of material properties down to the nanogram, picoliter, femtojoule, and attomole level. Combining various operating modes enables one to detect different interaction strengths with analytes and permits analysis of a variety of signal domains. Consequently, microengineering technologies have been used to design and fabricate a **N**anotechnology **o**lfactory **se**nsor device (NOSE) consisting of cantilever arrays with a volume of only $\approx$1 mm^3. Cantilever-based micromechanical devices operate in various media with high speed and sensitivity even in noisy environments, and offer applications, for example, to oenology or fragrance design.

I. INTRODUCTION

Millisecond, micrometer, nanonewton, picoliter, femtogram, attojoule and zeptomole — is there any need to measure these quantities? From my point of view: Yes, there is an immense need to sense even tiniest quantities, which are inaccessible to our senses, in our scientific, technical, and everyday environment. We increasingly need to

- probe phenomena in the "nanoworld",
- control online processes,
- detect harmful substances,
- test and design novel drugs,
- enhance safety and security.

Before elaborating on the functionality of micromechanical cantilever sensors, let me point out that some living species have developed highly specialized organs to detect smallest quantities. This enables them to survive in very specific circumstances, and we can learn from their faculties and transduction mechanisms.

II. LIVING SPECIES

Most living species possess five senses — sight, smell, taste, hearing, and touch (Figure 1). Some species are even known to have a sixth sense, which can detect and use geomagnetic fields for orientation [1].

Examples will be presented to show how certain species have adapted to specific life situations, how enormously sensitive environmental properties can be measured, and how essential it is for these living beings to detect signals on an extremely small scale in the presence of high background noise.

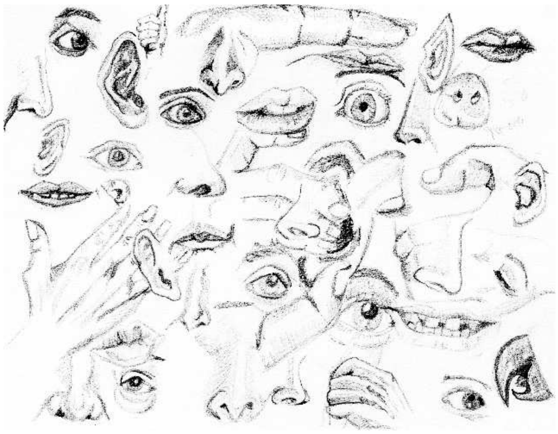


FIG. 1. *The five senses:* © G. Schwarz

A. Melanophila

It is known that *Melanophila* beetles, or "fire bugs", approach forest fires in large numbers from long distances. The biologist E.G. Linsey reported [2]: "*[Melanophila beetles] sometimes fly in unbelievable numbers to forest fires, burning refuse dumps, refineries, smelter plants etc. They normally breed in the fire scarred pines and under ordinary conditions they are rarely encountered in nature. Mating and oviposition often take place while the fire is still burning*". The reason for this behavior is that *Melanophila* larvae can develop only in freshly burnt wood. Therefore the beetles must be able to detect forest fires even at long distances to guarantee their continued existence. It was demonstrated that *Melanophila* respond to infrared light and do not use olfactory or auditory cues to detect forest fires [3]. Recently, the pit organs, which are schematically outlined in Figure 2, of these insects were examined [4,5].

The spheres of the pit organs consist of organic molecules having methyl and hydroxyl groups, which preferentially absorb infrared light at a wavelength typical of forest fires. The absorbed light is converted within a fraction of a millisecond into heat which causes a change in the cuticular sphere volume of pit organ. This change is thought to induce a deformation of the order of 1 nm, which triggers a response of the insects' sensory neuron.

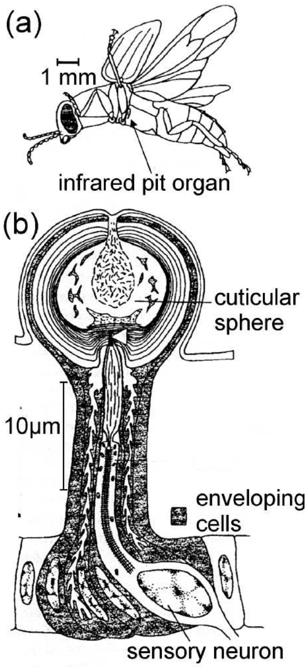


FIG. 2. (a) During flight, the infrared pit organs of *Melanophila* beetles are exposed and enable the insect to steer troptactically toward the heat source. (b) Infrared sensillum. From [5].

The mechanoreceptors allow *Melanophila* to detect forest fires from distances of up to 50 km, which is of essential biological relevance for this insect.

B. Exoskeletal Sensors for Walking

When an animal walks, its organism must measure the load on its legs to control the walking process. Arthropods have sensilla built into their exoskeleton, which allow them to detect pressure, gravitational forces, and vibrations of the ground. The most intriguing version known of such a mechanical sensing apparatus is that of spiders, which have what are called slit sensilla [6], located close to the joints of their legs (Figure 3a). These slit sensilla, which range in size from 10 to 150 μm (Figure 3b), are compressed by forces perpendicular to their lengthwise axis. As the pre-bent outer membrane is bent further, a deformation of the dendrite tip (de), which has a diameter of less than 1 μm, occurs within the coupling cylinder (cy) [6]. This

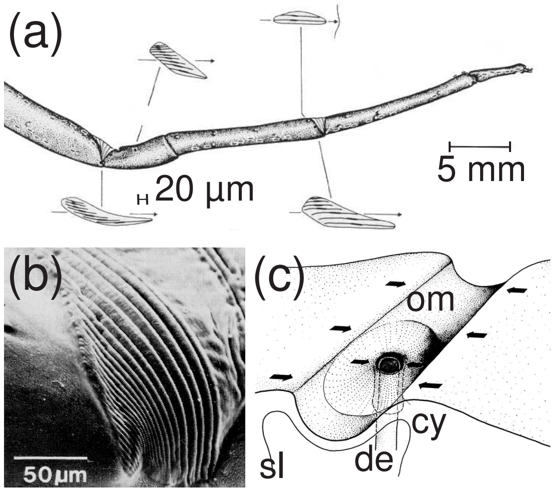


FIG. 3. (a) Distribution of slit sensilla in the exoskeleton of the spider *Cupoennius salei*. (b) Scanning electron microscopy (SEM) image of the slit sensilla (sl). (c) Schematic principle of the transduction mechanism of the applied force (arrows) on the slit (sl). This force bends the outer membrane (om), which deforms the dendrite tip (de) within the coupling cylinder (cy). From [6].

deformation is then transduced into an electrical response, resulting from a change in ion flux [7]. The high sensitivity of slit sensilla, which can measure displacements as small as 1 nm, is due to special features of this mechanical transduction mechanism. First, owing to its elongated shape, the slit is most easily deformed by forces perpendicular to its lengthwise axis. Second, owing to its arched cross section the covering membrane is bent further most effectively by lateral forces acting on it during slit compression. Third, the coupling cylinder is attached to the bottom of the covering membrane, i.e. where the bending is strongest.

C. Bombyx Mori

The female *Bombyx mori* silkworm emits vapors of bombycol, a pheromone (H_3C-$(CH_2)_2$-$(HC{=}CH)_2$-$(CH_2)_9$-OH), to attract males for propagation. The male silkworm has receptors located in its antennae, shown in Figure 4. Approximately 1000 bombycol

FIG. 4. The male *Bombyx mori* silkworm has long antennae on its head to detect pheromone from the female silkworm. From [8].

molecules in the natural environment of a male silkworm are sufficient to cause reactions in its receptors, which enable it to locate the female [9].

Examination of these examples of living species has revealed how mechanical transduction on a micrometer scale can be extremely sensitive to infrared radiation, and local stress changes, and how olfactory detection can be specific on a molecular scale. These striking examples raise questions regarding whether one can design and fabricate sensors to extend the capability of the natural senses to a similar degree of sensitivity to detect heat, stress, and mass down to the level of individual molecular events.

III. MICROMECHANICAL CANTILEVER SENSORS

In science and technology, methods have been developed to improve our human senses by several orders of magnitude and to objectify them. *Sight* is extended by optical microscopes, for example by a scanning near-field optical microscope [10], which has a spatial resolution in the nanometer realm, or a photomultiplier, which has the capability to detect single photons [11]. On the other hand, when objects at large distances are to be investigated, telescopes have been built to observe phenomena in galaxies that are millions of lightyears away from the earth. *Hearing* can be enhanced by microphones whose performance is extended into ultrasound. Recently, an artificial cochlea was proposed that uses micromechanical membrane sensors having different lengths which respond to sound [12]. Tactile senses (*touch*), the ability to feel rough and smooth surfaces, has been extended in an unprecedented way by the scanning force microscope (SFM) [13]. Using this technique, forces of only a few piconewtons can be measured, e.g. forces occuring during the unfolding of individual titin immunoglobulin domains [14]. The capability of extending the performance of the human senses of *taste* and *smell* by using SFM techniques is subject of this paper. Currently attainable and theoretically possible detection limits will also be discussed.

Fundamental reasons for promoting micromechanical systems [17] for research and development are, first, that almost every signal domain such as force, heat, stress, magnetism, charge, radiation, and chemical reactions can be readily transduced into a micromechanical deflection by an appropriately coated structure. Second, silicon-based micromechanical devices, can be integrated into microelectronic processing systems such as complementary metal oxide semiconductors (CMOS) [18]. This enables seamless sensors to be fabricated at low cost and allows them to be integrated directly into computer based data-acquisition. Third, typical cantilever sensors, shown in Figure 5, are extremely small, which results in a short response time (ms) and a sensitivity far superior to that achievable with standard techniques. The transduced micromechanical deflection of the sensor can be read out with picometer accuracy over a wide range on the micron scale by using SFM techniques [19]. A frequently used method is to measure the displacement of a laser beam reflected off the cantilever as schematically illustrated in Figure 6.

Another technique that is compatible with integration into micromechanics and is also capable of measuring tiny deflections uses the piezoresistive effect to probe deflections of cantilevers in SFM [20] and in sensors [21,22]. A promising method for sensing deflections relies on thin piezoelectric layers deposited on the cantilever [23]. Microfabricated capacitive sensors [24] or interdigital cantilevers [16] were also used to track deflections and have potential applications for sensors.

To detect heat, radiation, gases, flow, or vapors of volatile molecules, these effects have to cause a micromechanical deflection of the cantilever. The transduction mechanisms of signals with cantilever-based sensors are summarized as operating principles in Figure 7 [25]. In the following, details of these transduction mechanisms will be elucidated.

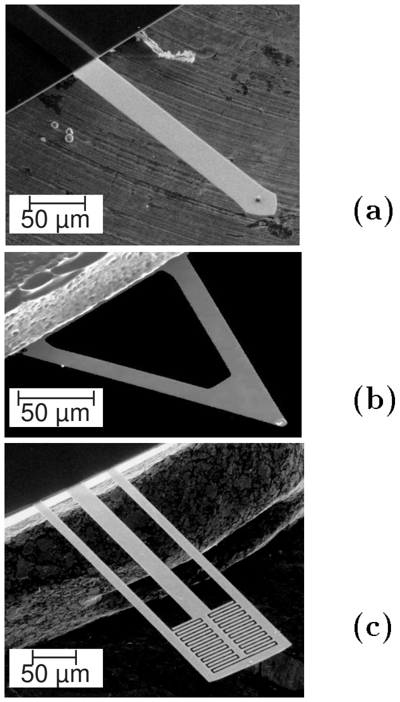


FIG. 5. Scanning electron micrograph showing three types of cantilever sensors usually applied for scanning force microscopy. (a) Single-beam Si cantilever sensor, 450 μm long, 40 μm wide and 1.5 μm thick. (b) "V"-shaped SiN_x sensor, 180 μm long, 18 μm wide and 0.6 μm thick [15]. (c) Interdigital fingers of the sensor form a diffraction grating [16].

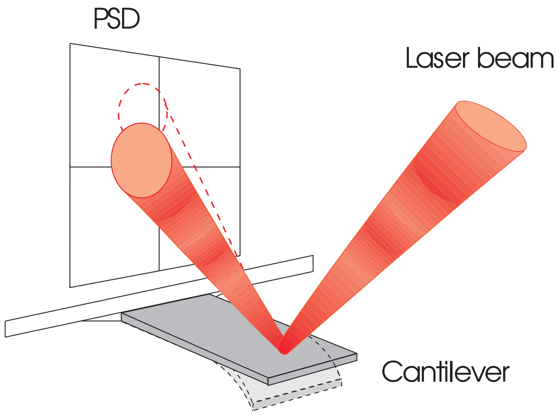


FIG. 6. Principle of the beam deflection technique: A semiconductor laser beam is focused with a spot size of 20-30 μm on the apex of the cantilever. The reflected laser beam is guided onto a position-sensitive detector (PSD), such as a quadrant photodetector. The position of the laser beam spot on the PSD is a known function of the sensor bending.

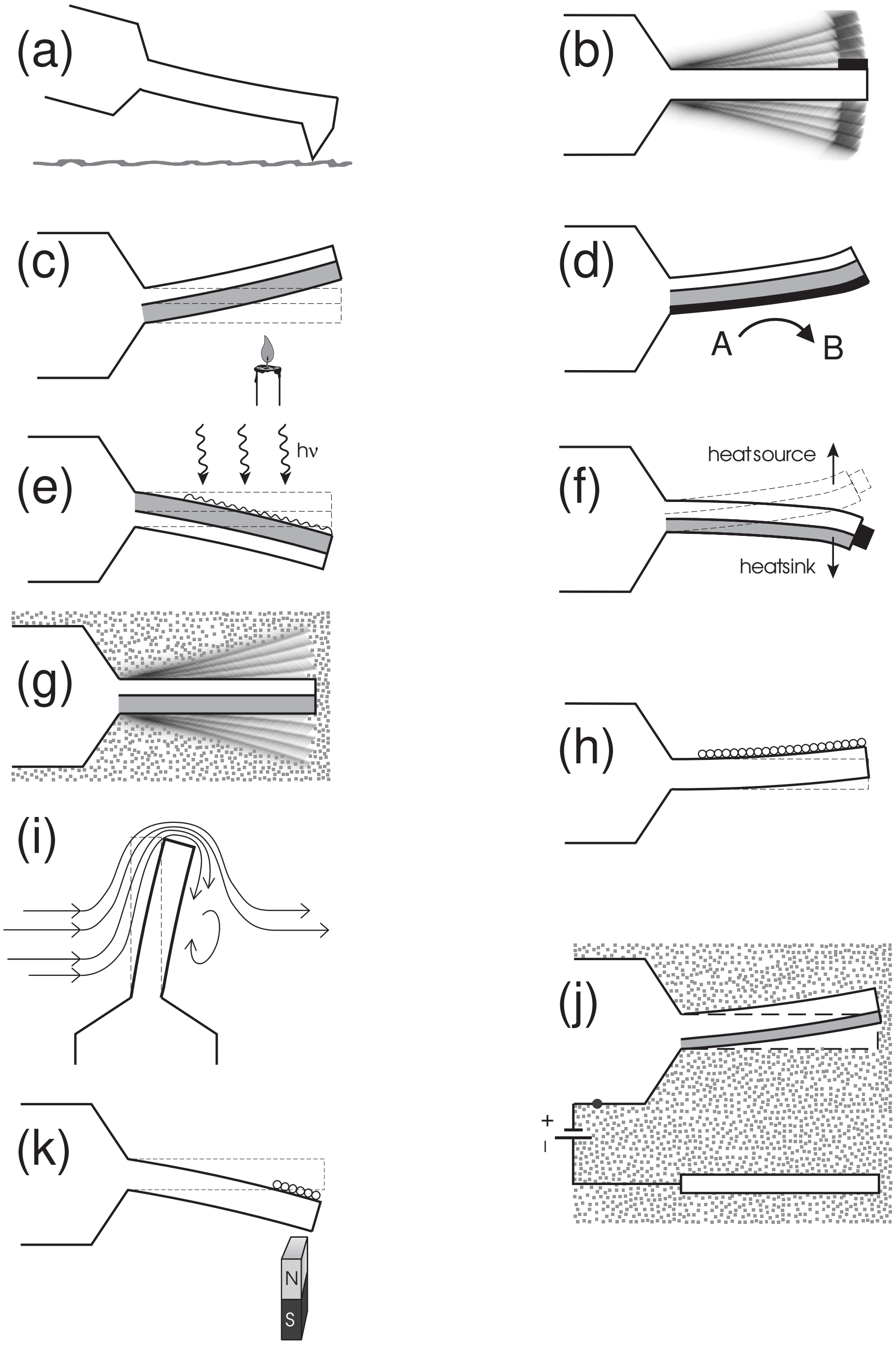


FIG. 7. Schematics of various operational principles of micromechanical cantilever sensors in side view. These sensors can be applied for: (a) atomic force sensors, (b) microbalances, (c) temperature sensors, (d) catalytic reaction sensors, (e) photothermal sensors, (f) calorimeters, (g) environmental sensors, (h) surface stress sensors, (i) flow sensors, (j) electrochemical sensors, and (k) magnetization sensors.

IV. THERMOGRAVIMETRIC ANALYSIS

Cantilever-based sensors can be vibrated by a piezoelectric actuator to resonate, which allows to operate the cantilever as a microbalance to weigh and monitor the change of mass of attached samples (Figure 7b). For quantitative analysis of masses, two types of loading on the sensor surface have to be distinguished: continuous loading (CL) on the entire cantilever surface (Figure 8a) and local loading within a defined area on the cantilever, e.g. towards the apex (AL) as sketched in Figure 8b. When molecules adsorb in a CL

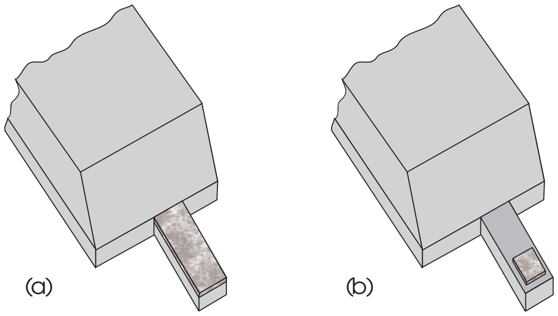


FIG. 8. Surface of a cantilever sensor can be (a) continuously coated (CL) by a specific adsorbing or desorbing material or (b) coated only at the apex (AL).

configuration, the mass change effect can interfere with changes of the mechanical properties, such as the stiffness, of the specific sensing overlayer upon adsorption. Experiments using a gelatine-coated sensor have shown to be very sensitive to humidity, where adsorption of water causes an increasing resonance frequency of the sensor [26–28], which is in contradiction to the increasing mass. This crosstalk to mass loading can be minimized by restricting the sensitive area to a narrowly defined location on the cantilever surface. The layer mass change, Δm, in an AL configuration is determined by

$$\Delta m = \frac{K}{4\pi^2}\left(\frac{1}{f'^2} - \frac{1}{f^2}\right) \quad , \qquad (1)$$

where f is the resonance frequency before adsorption, f' is the resonance frequency during adsorption, and K the sensor spring constant [29]. Restricting the sensitive layer reduces the amount of molecules adsorbed, which results in a smaller mass change and hence a smaller resonance frequency shift of the sensor. To overcome this loss of sensitivity the apex of the sensor can be loaded with a microporous material having a high surface-to-mass ratio.

Zeolite materials are nanoporous, selective for molecular shapes [30], and are used for catalysis [31]. Zeolites have been demonstrated to enhance the sensitivity of micrometer-scale devices to loading [32].

The sensitivity of a cantilever to mass loading is mainly determined by the selected resonance frequency [33]. Theoretical estimations based on commercially available cantilevers have revealed that these microbalances feature a sensitivity to mass loadings down to a minimum detectable mass of only $\approx 10^{-16}$ g [34]. Molecular loading from the environment onto the sensor is determined by temperature, T. In addition to adsorption effects the attached sample can be chosen to undergo temperature-dependent mass changes such as desorption or decomposition. Heating the micromechanical device allows one to probe temperature-dependent effects of the sample-environment system. Simultaneously heating the cantilever sensor and measuring the resonance frequency enables one to investigate the temperature-dependent mass desorption (dm/dT) characteristics of picoliter volume samples,

$$-\frac{1}{f}\frac{df}{dT} = \frac{1}{2m}\frac{dm}{dT} - \frac{1}{2K}\frac{dK}{dT} \quad , \qquad (2)$$

where dK/dT is a sensor calibration factor. Quantitative analysis requires careful calibration of cantilever properties and positioning of the attached sample [35]. For thermogravimetric applications one strongly benefits from the short thermal response time of micromechanical devices, which can be heated within a few milliseconds to temperatures of ≈ 1000 °C [35]. The desorption characteristics of a tiny specimen attached to the heatable sensor was analyzed using a picoliter volume of a standard calibration substance, $CuSO_4 \cdot 5H_2O$ [35].

V. 'BIMETALLIC' SENSORS: PHASE TRANSITIONS

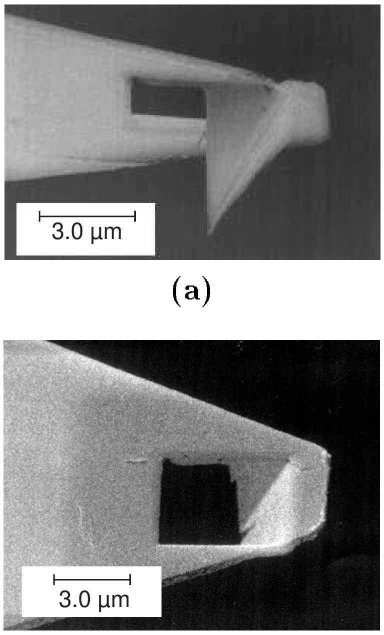
The performance of the cantilever sensor is extended to that of a calorimeter by depositing a metal layer onto the cantilever beam. Two layers having different thermal expansion coefficients form a sensor via the bimetallic principle. The vertical deflection, z, of the sensor is given for a heating at the apex by

$$\Delta z = \frac{t_1 + t_2}{t_2^2 K} \frac{(\alpha_1 - \alpha_2) l^3 P}{w(\lambda_1 t_1 + \lambda_2 t_2)} \quad , \qquad (3)$$

[36], where λ_1, λ_2 are the thermal conductivities, α_1, α_2 are the thermal expansion coefficients, t_1, t_2 are the thicknesses of the sensor layers, P is the power generated at the apex, w is the width and l the length of the sensor. Such micromechanical devices are able to detect temperature variations as small as 10^{-5} K (Figure 7c) and can be calibrated in-situ [37]. 'Bimetallic' cantilevers have been applied to study the heat evolution in catalytical chemical reactions [37] (Figure 7d) and have been extended to perform photothermal spectroscopy with a sensitivity of 150 fJ (Figure 7e) [38]. Theoretical estimations have shown that these sensors are able to detect heat changes with attojoule sensitivity [21] by attaining a thermal response of milliseconds [37].

These sensor types have been applied to perform thermal analysis of picoliter volumes of alkanes (Figure 7f). Such small quantities are inaccessible to standard thermal analysis [39]. The mass of the attached sample is determined from a resonance frequency analysis of the sensor. Enthalpy changes associated with phase transitions in a nanogram samples of alkanes were detected and determined quantitatively [40]. This technique extends the analysis of small quantities of material to the nanogram realm, where size-dependent properties of samples can be studied [41].

A well-defined microbeaker can be fabricated from the SFM tip at the apex of the cantilever by using focused ion beam milling [42],



(b)

FIG. 9. Scanning electron micrographs of a modified SFM SiN_x-tip wall. The inside is empty and resembles a shovel of micrometer size. (a) Viewed from the top and (b) from the side.

as demonstrated in Figure 9. This picoliter shovel was scanned over a surface and can be used at higher loading to collect material from the surface. After the shovel has been filled, thermal analysis could be performed to detect, for example, characteristic temperatures of phase transition. This technique could be used to obtain specific chemical information about the material composition at surfaces.

The 'bimetallic' sensor can also be operated in liquid environments. Measurements in a vacuum, air, and ethanol environment using identical sensors have revealed a response time in the millisecond realm by attaining a sensitivity in the nanojoule realm [43]. Applications are in the field of detecting environmental properties such as pressure or viscosity [44] (Figure 7g).

The position of the laser spot on the cantilever (see Figure 6) determines the signal regime to be measured. The device can be operated to be sensitive to cantilever temperature changes and by moving the laser towards the cantilever apex the sensor can be used to detect volume changes in overlayers [40]. Such experiments were performed on attached samples, which undergo structural phase transitions, in particular a solid-solid phase transition and a solid-liquid phase transition in alkanes [40,45].

VI. MOLECULAR ADSORPTION ON SPECIFICALLY COATED SENSOR SURFACE

The magnitude of bending signals associated with structural phase transitions in alkanes was measured to be ≈20 times higher than that of transient transition heat. Surface stress changes on one side of a cantilever also cause a permanent bending (Figure 7h), which was first reported by the physicist G.G. Stoney [46], who " ... *found that when nickel was deposited on one side of a thin sheet of metal very considerable bending took place*". The surface stress change $\sigma_s = \sigma t_f$ due to an overlayer of thickness t_f can be determined from the cantilever curvature radius R using Stoney's formula [46]

$$\sigma = \frac{E t_s^2}{6R(1-\nu)t_f} \quad , \tag{4}$$

where E is Young's modulus, t_s is the sensor thickness and ν is Poisson's ratio of the sensor material. This transduction mechanism requires specific coating of the cantilever on one side, which binds only specific molecules. Such sensitive coatings can be tailored to bind molecules in a preferential and specific manner [47]. Promising candidates for designer surfaces are based on alkanethiol molecules, which are known to self-organize into well-ordered, densely packed films [48–50]. These self-assembled monolayers (SAMs) are used in applications such as microcontact printing [51] and voltametric microsensors [52], and have recently been applied to molecular host–guest recognition [53]. Surface stress changes were measured in-situ during the self-assembly of alkanethiols on gold using a micromechanical sensor [54]. In particular, the kinetics of SAM formation is analyzed and the replacement process of adsorbates by butanethiol molecules is studied [55]. SAMs of methyl-terminated alkanethiol SAM, $CH_3(CH_2)_{n-1}$-$\mathbf{CH_3}$, can be substituted by an ω-functionalized mercaptohexadecanoic-acid SAM, $CH_3(CH_2)_{n-1}\mathbf{COOH}$, on gold. The principle of ω-functionalized molecules enables the detection of specific molecules by docking a guest molecule at the monolayer air interface via the key-lock principle, which is schematically outlined in Figure 10 [53,56]. In particular the influence of hexylamine molecules docking from the vapor phase onto a mercaptohexadecanoic-acid SAM was studied [54].

The technique outlined here demonstrates the concept of probing surface stress changes in monomolecular systems. In the limit of the smallest detectable bending of standard-sized, commercially available cantilever sensors, surface stress changes of 10^{-7} Nm^{-1} can be probed. This corresponds to a change of zepto (10^{-21}) molar quantities on the sensor. A further reduction of the sensor thickness into the nanometer realm [57] promises detection limits of even smaller quantities. There is in principle no fundamental barrier to preclude the application of the described technique to detect individual molecular events. Experiments applying biosensing techniques have been reported which have

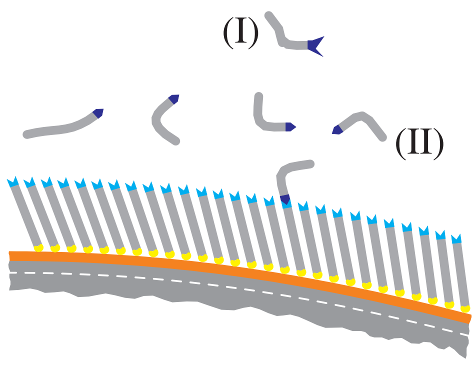


FIG. 10. Sketch of the sensor, side view, showing the bent sensor and the molecular receptor layer. Only molecules with the appropriate structure (II) can bind to the receptor layer, ideally via a perfect key-lock principle. Other molecules (I) cannot bind to these receptors. The dashed line indicates the curvature radius of the sensor.

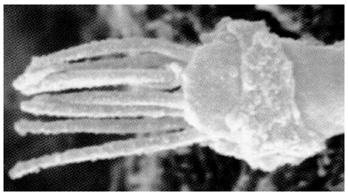
applied the switching of the conductance of molecular ion channels to detect individual molecular events [58]. Those experiments could enable thermal noise to be overcome.

VII. CHEMICAL "NOSE"

Taste and *smell* are perhaps the most evocative senses a human being has: We can remember the characteristics of smells and tastes years later and can associate them with specific events and locations. But also each individual has a unique characteristic scent. Smells are not pure substances, but complex mixtures of various molecules. For example there are some 700 different chemical vapors in a glass of beer, yet somehow we can take a sniff and say it's beer. The vapor components and their interaction are responsible for characteristic scents. The interpretation of mass spectrometry data, where substances are disassembled into their molecular units and detected at very high sensitivities, is difficult when the quality of beer is to be evaluated.

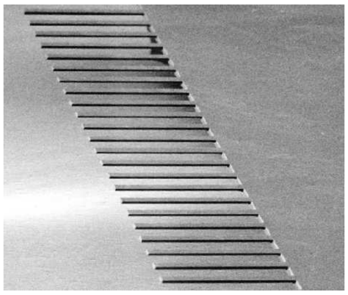
A human first detects an odor at the olfactory epithelium in the upper region of the nose, where odor molecules bind to receptors on hairlike cilia. Figure 11a shows the hairlike cilia protruding from the tip of an individual sensory neuron in the human olfactory epithelium [59]. Humans are believed to be able to differentiate up to ≈10,000 scents (e.g. oenologists or fragrance designers), whereas some animals, for example the bloodhound, are even more sensitive to odors and are able to distinguish two orders of magnitude more scents [59].

Artificial electronic noses may help us to analyze and characterize smells. One example of an artificial nose is the use of fiber array tips coated with various polymer dye molecules. These coatings show fluorescent responses depending on the present mixture of vapors. Recorded video signals of the temporal responses were then used to train a neural network for vapor recognition [60]. Other principles for electronic noses are based on the application of surface acoustic



(a)

(b)



(c)

FIG. 11. (a) A scanning electron micrograph of the hairlike cilia (lengths are ≈25 nm) [59], which protrude from the tip of an individual neuron, is shown for camparison to two sensor arrays fabricated for the "NOSE" device. (b) Thin sensor arrays favor detection of analytes via surface stress changes. The fabricated silicon sensors have a thickness of 0.8 μm, a length of 500 μm and a pitch of 250 μm. (c) Thicker sensors are suitable for detecting analytes in the dynamic mode. Part of a 28-cantilever array chip is shown. The lateral geometries are identical to those of the array shown in (a) but the thickness of the cantilevers is 3.5 μm.

wave (SAW) devices, quartz crystal microbalance (QCM) devices etc. For an overview of electronic noses and products on the market, the reader is referred to the literature [61–63].

Using the high sensitivity, the short response time, the tiny size of and the experience obtained with single cantilever-based sensors, **N**anotechnology **o**lfactory **se**nsor

(NOSE) arrays have been designed and fabricated. Arrays of these micromechanical cantilever arrays are shown in Figure 11 b&c. Different operating modes and molecular receptor layers can be combined into one micromechanical chip that supports an array of individually coated sensors. Examples of receptor layers are metals (Pt, Ni, etc.) [64], self-assembled ω-functionalized monolayers [54,55,65], polymer thin films [66] or micro/-nanoporous materials [32,35]. Using different receptor layers enables one to detect different strengths of interactions with flavors. The various operating modes provide detailed information due to different transduction mechanisms of a given flavor with the receptor layer such as mass, heat, or strength of binding, as described in previous sections. In contrast to other techniques, all operating modes can be integrated on a single chip, leading to a very small sensor device ($\approx$1 mm^3).

To detect a specific reaction on the sensor elements, each one has to be read out individually. This was achieved with a sequential readout technique by using a fiber array ribbon [67,68]. In comparison with single sensors it is found that mechanical disturbances from noise, such as from vibrations, turbulent gas flow (Figure 7i [69], or abrupt pressure changes, can be effectively removed with array sensors by recording difference signals with respect to reference cantilevers. In experiments performed in noisy environments, such as gas flow, mechanical vibrations etc., signals can be restored and display the typical characteristics of the specific interaction of the analyte gas and the specifically coated sensor element [67,68]. The diffusion of various alcohols into poly-methyl-methacrylate (PMMA) induces resonance frequency shifts in a dynamic measuring mode and a bending in the static stress mode, which allows to distinguish amongst various alcohols [67,68]).

In the reported experiments the sensitive layer was electron-beam-deposited (Pt) or spray-coated (PMMA), by using shadow masks aligned on top of the sensor chip. The mask leaves only particular sensor elements exposed to the evaporation process. A more elegant way to coat the sensor with specific molecules is to use a microfluidic network [70,71], which can be filled with appropriate solvents that carry the receptor substance (Figure 12). The array sensors were coated by alkanethiols by immersing them into the filled network and retracting them within a few seconds after a certain reaction has taken place.

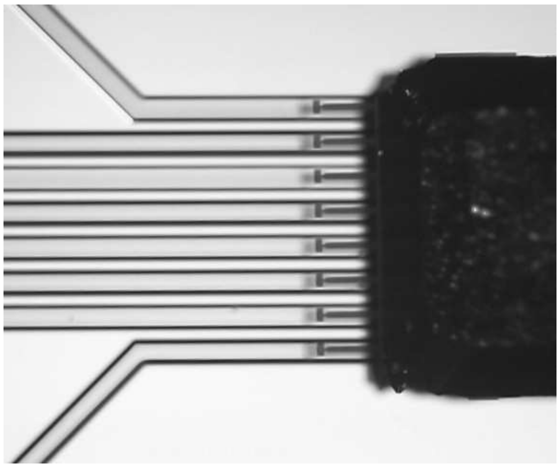


FIG. 12. This optical micrograph shows the cantilever array above the microfluidic network filled with hexadecane. The pitch of the microfluidic network as well as of the cantilevers is 250 μm.

VIII. SUMMARY, OUTLOOK AND PERSPECTIVES

The transduction principles outlined here can be extended to probe surface stress changes electrochemical environment [72,73] (Figure 7j). Magnetic forces acting on a paramagnetic sample were mechanically detected by magnetic resonance techniques [74] and torque magnetometry [75] (Figure 7k). The kind of transduction principles shown in Figure 7 are by no means complete. Further techniques, perhaps using more specifically designed microstructures, will extend the number and signal domains transduced into a micromechanical motion.

Compared to the mechanical transduction mechanisms used by insects and spiders, the micromechanical approach outlined here also reveals a very high performance in terms of sensitivity as well as speed. The highest sensitivity in terms of numbers of molecules was observed in the stress mode, where zeptomolar quantities are theoretically detectable. All transduction mechanisms and operating principles outlined can be employed simultaneously on only one device to obtain "orthogonal information". This means that signals from different analytes may cause similar responses in one operating mode, but different behavior in another mode. This will allow one to distinguish between similar but non-identical chemical compounds.

FIG. 13. Dr. McCoy inspecting the "NOSE" with his assistant. © Star Trek.

Ultraprecise measurement tools are necessary components of most scientific and engineering enterprises. They are highly desirable for forensic and related chemical analysis. The performance of the device presented here lends it to applications in process control and online monitoring, such as the detection of harmful substances in our environment. Because cantilever sensors also work in liquid environments and can be biocompatible, they can be used for biochemical and medical analysis. The size of the sensor and therefore also of the sensitive layer are very small, which minimizes the pollution of the analyte by sensor materials. The previously stated advantage of their low cost, owing to mass production, makes these sensors highly attractive. This will permit disposable devices to be used for various specific applications.

The future may bring us the kind of invivo diagnostic tools that would seem perfectly commonplace in an episode of *Star Trek* with sensors that emit an alarm when one is coming down with a disease. If this is realized then physicians would only need a scanner to perform non-invasive diagnostics. Even online analysis and medical indications obtained from a signal of a chip built in a computer which is connected to the World Wide Web are conceivable scenarios for the future.

IX. ACKNOWLEDGEMENTS

I first address my thanks to Dr. Ch. Gerber, Dr. J.K. Gimzewski, Prof. Dr. E. Meyer, Dr. H.P. Lang, and Prof. Dr. H.-J. Güntherodt, who continuously supported me during my PhD work. I strongly benefited and learned from their scientific perspectives, skills, and knowledge. In particular, Dr. Ch. Gerber and Dr. J.K. Gimzewski always helped me by way of discussions to find the most straightforward and clearest way to conduct experiments and to solve experimental problems. I also want to add that working at IBM Rüschlikon was a real pleasure for me. In lieu of all those who provided the ideal research environment for me at IBM, I want to thank Dr. P. Guéret.

Additionally, I am grateful to my colleagues in the microcontact printing group for their experimental collaboration and their insights into the magic of chemistry. Specifically, I thank Dr. E. Delamarche and Dr. H. Biebuyck for their profound knowledge and experimental skill.

I am deeply grateful to my colleagues in the micromechanics team, C. Andreoli, Dr. J. Brugger, Dr. M. Despont, U. Drechsler, and Dr. P. Vettiger, for their scientific and technical support in providing me with various micromechanical sensors.

Within the MINAST collaboration, I want to give my warmest thanks to Dr. L. Scandella and J.H. Fabian, who supported me throughout the experiments, in particular with respect to the microbalance sensors, and also for providing special zeolite samples.

I am also happy to acknowledge Dr. J. Fompeyrine for obtaining and evaluating the data of all our three-day-and-night experiments, as well as Dr. J.-P. Locquet for the many theoretical and experimental discussions of layered structures. He provided insight into potential applications of these materials.

Moreover, I thank Dr. T.A. Jung for his continuous help with all kinds of problems and for explaining various things that were new to me.

I also thank all the colleagues with whom I had the pleasure of working and discussing, and from whose knowledge I benefited (in alphabetic order): Dr. S.F. Alvarado, Dr. D. Anselmetti, Dr. F. Arrouy, Prof. Dr. H. Baltes, F. Battiston, Dr. P. Bauer, Dr. A. Beck, Prof. Dr. J.G. Bednorz, A. Bernard, A. Bietsch, Dr. P.E. Blöchl, Dr. M.T. Cuberes, A. Daridon, Dr. U. Dürig, J. Fritz, Dr. K. Gulden, W. Häberle, T. Haeusler Dr. H. Hilgenkamp, Dr. A. Koll, D. Lange, Dr. V. Langlais, Dr. M. Lutwyche, E. Mächler, S. Manalis, Prof. Dr. J. Mannhart, Dr. M. Mattner, Dr. B. Meyer, G.I. Meijer, Dr. B. Michel, Dr. D. Nyfeler, Prof. Dr. H. Rohrer, C. von Scala, G. Schrag, Dr. S. O'Shea, J. Perret, J.P. Ramseyer, H. Riel, Dr. Ch. Rossel, R.R. Schlittler, H. Schmid, and P. Trommler.

I also very gratefully acknowledge the help from the publications department of IBM (L.M. Pavka, Ch. Bolliger, W.R. Cideciyan, and C. Griggs) for their help in eliminating Germanisms from my English and for editing manuscripts. U. Bitterli and D. Kropaci are also warmly thanked for their support and endurance in preparing figures.

The help of people from "UNIPHASE", A. Brönnimann, K. Dätwyler, H. Rotfritz, B. Mayer, B. Münch, and P. Riel and for the use of their experimental equipment is also acknowledged.

Finally, my special thanks for the continuous support from my private environment such as my parents and G. Schwarz. The latter I want to thank for her patience with the unfortunately again minimal time spent together. G. Schwarz is also gratefully acknowledged for the graceful painting, shown in Figure 1.

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[1] K.J. Lohmann, *How Sea Turtles Navigate*, Scientific American, 82, January (1992).

[2] E.G. Linsley, *Attraction of Melanophila Beetles by Fire and Smoke*, Journal of Economic Entomology **36**, 341 (1934).

[3] W.G. Evans, *Perception of Infrared Radiation from Forest Fires by Melanophila Acuminata de Geer (BUPRESTIDAE, COLEOPTERA)*, Ecology **47**, 1061 (1966).

[4] T. Vondran, K.-H. Apel, and H. Schmitz, *The Infrared Receptor of Melanophila Acuminata De Geer (Coleoptera: Buprestidae): Ultrastructural Study of a Unique Insect Thermoreceptor and its Possible Descent from a Hair Mechanoreceptor*, Tissue & Cell **27**, 645 (1995).

[5] H. Schmitz, H. Bleckmann, and M. Mürtz, *Infrared Detection in a Beetle*, Nature **386**, 773 (1997).

[6] F.G. Barth, *Slit Sensilla and the Measurement of Cuticular Strains*, in Neurobiology of Arachnids, edited by F.G. Barth, Springer Heidelberg 1985.

[7] F. Sachs, *Mechanical Transduction in Biological Systems*, CRC Critical Reviews in Biomedical Engineering **16**, 141 (1988).

[8] T. Haeusler, *Künstliche Nasen/ Maschinen mit gutem Riecher*, FACTS **16**, 116 (1997).

[9] Herder Lexikon der Biologie, Band 2, Red. Udo Becker et al. Spektrum Akademischer Verlag (1994).

[10] D.W. Pohl, W. Denk, and M. Lanz, *Optical Stethoscopy: Image Recording with Resolution $\lambda/20$*, Appl. Phys. Lett. **44**, 651 (1984).

[11] Hamamatsu, *How to Perform Photon Counting*, Technical Information, Feb. 1992.

[12] D. Haronian, and N.C. MacDonald, *A Microelectromechanical Based Artificial Cochlea (MEMBAC)*, Proceedings of the 8th International Conference on Solid-State Sensors and Actuators, and Eurosensors, Stockholm, Sweden, June 25–29 (1995).

[13] G. Binnig, C.F. Quate, and Ch. Gerber, *Atomic Force Microscopy*, Phys. Rev. Lett. **56**, 930 (1985).

[14] M. Rief, M. Gautel, F. Oesterhelt, J.M. Fernandez, and H.E. Gaub, *Reversible Unfolding of Individual Titin Immunoglobulin Domains by AFM*, Science **276**, 1109 (1997).

[15] Nanosensors GmbH, Aidlingen, Germany; Park Scientific Instruments, 1171 Borregas Avenue, Sunnyvale, CA; Digital Instruments, 520 E. Montecito St, Santa Barbara, CA.

[16] S.R. Manalis, S.C. Minne, A. Atalar, and C.F. Quate, *Interdigital Cantilevers for Atomic Force Microscopy*, Appl. Phys. Lett. **69**, 3944 (1996).

[17] J.W. Gardner, *Microsensors*, New York 1994.

[18] H. Baltes, and C.A. Leme, in *Micro- and Nanosensor Technology/Trends in Sensor Markets,* W. Göpel, J. Hesse, J.N. Zemel (eds.) Vol. 8 (VCH, Weinheim, 1995).

[19] D. Sarid, *Atomic Force Microscopy* (Oxford Univ. Press, New York, 1991).

[20] F.J. Giessibl, and B.M. Trafas, *Piezoresistive Cantilevers Utilized for Scanning Tunneling and Scanning Force Microscope in Ultrahigh Vacuum*, Rev. Sci. Instrum. **65**, 1923 (1994).

[21] E. Meyer, J.K. Gimzewski, Ch. Gerber, and R.R. Schlittler, *Micromechanical Calorimeter with Picojoule-Sensitivity*, in *The Ultimate Limits of Fabrication and Measurement*, M.E. Welland and J.K. Gimzewski (eds.), NATO ASI Series Vol. 292, 89-96 (Kluwer, Dordrecht, 1995).

[22] P.G. Datskos, P.I. Oden, T. Thundat, E.A. Wachter, R.J. Warmack, and S.R. Hunter, *Remote Infrared Radiation Detection Using Piezoresistive Microcantilevers*, Appl. Phys. Lett. **69**, 2986 (1996).

[23] T. Fujii, S. Watanabe, M. Suzuki, and T. Fujiu, *Application of Lead Zirconate Titanate Thin Films Displacement Sensors for the Atomic Force Microscope*, J. Vac. Sci. Technol. **B 13**, 1119 (1995).

[24] N. Blanc, J. Brugger, N.F. de Rooij, and U. Dürig, *Scanning Force microscopy in the Dynamic Mode Using Microfabricated Capacitive Sensors*, J. Vac. Sci. Technol. **B 14**, 901 (1996).

[25] R. Berger, H.P. Lang, Ch. Gerber, J.K. Gimzewski, *Micromechanics: A Toolbox for Femtoscale Science: "Towards a Laboratory on a Tip"*, Microelectronic Engineering **35**, 373 (1997).

[26] T. Thundat, R.J. Warmack, G.J. Chen, and D.P. Allison, *Thermal and Ambient-Induces Deflections of Scanning Force Microscope Cantilevers*, Appl. Phys. Lett. **64**, 2894 (1994).

[27] E.A. Wachter, and T. Thundat, *Micromechanical Sensors for Chemical and Physical Measurements*, Rev. Sci. Instrum. **66**, 3662 (1995).

[28] T. Thundat, E.A. Wachter, S.L. Sharp, and R.J. Warmack, *Detection of Mercury Vapor Using Resonating Microcantilevers*, Appl. Phys. Lett. **66**, 1695 (1995).

[29] The spring constants were calculated from the cantilever geometry, which was determined from scanning electron micrograph images. For details see E. Meyer, R. Lüthi, L. Howald, M. Bammerlin, M. Guggisberg, and H.-J. Güntherodt, *Instrumental Aspects and Contrast Mechanisms of Friction Force Microscopy*, in B. Bhushan, Ed., Micro/Nanotribology and Its Applications, NATO ASI Series E: Applied Sciences **330**, 193 (Kluwer, Dordrecht, 1997).

[30] T. Bein, *Synthesis and Applications of Molecular Sieve Layers and Membranes*, Chem. Mater. **8**, 1636 (1996).

[31] H. van Bekkum, E.M. Flanigen, and J.C. Jansen, Eds., *Introduction to Zeolite Science and Practice, Studies in Surface Science and Catalysis*, Vol. 58 (Elsevier, Amsterdam, 1991).

[32] L. Scandella, G. Binder, T. Mezzacasa, J. Gobrecht, J.H. Koegler, J.C. Jansen, R. Berger, H.P. Lang, Ch. Gerber, J.K. Gimzewski, *Zeolites: Materials for Nanodevices*, submitted to Microporous Materials (Sept. 97).

[33] H. Baltes, A. Koll, and D. Lange *The CMOS MEMS Nose - Fact or Fiction?*, IEEE International Symposium for Industrial Electronics ISIE'97, Portugal (1997).

[34] P. Oden, T. Thundat, and R.J. Warmack, *Gravimetric Sensitivity Comparison Between Acoustic Wave Microsensors and Microcan-*

tilevered Sensor Devices, submitted to Rev. Sci. Instrum. Nov.'97.

[35] R. Berger, H.P. Lang, Ch. Gerber, J.K. Gimzewski, E. Meyer, H.-J. Güntherodt, L. Scandella, *Micromechanical Thermogravimetry*, submitted for publication (Nov. 97).

[36] J.R. Barnes, R.J. Stephenson, C.N. Woodburn, S.J. O'Shea, M.E. Welland, T. Rayment, J.K. Gimzewski, and Ch. Gerber, *A Femtojoule Calorimeter Using Micromechanical Sensors*, Rev. Sci. Instrum. **65**, 3793 (1994).

[37] J. K. Gimzewski, Ch. Gerber, E. Meyer, and R. R. Schlittler, *Observation of a Chemical Reaction Using a Micromechanical Sensor*, Chem. Phys. Lett. **217**, 589 (1994).

[38] J.R. Barnes, R.J. Stephenson, M.E. Welland, Ch. Gerber, and J.K. Gimzewski, *Photothermal Spectroscopy with Femtojoule Sensitivity Using a Micromechanical Device*, Nature **372**, 79 (1994).

[39] W. Hemminger, and G. Höhne, *Calorimetry* (Chemie, Weinheim, 1984).

[40] R. Berger, Ch. Gerber, J.K. Gimzewski, E. Meyer, H.-J. Güntherodt, *Thermal Analysis Using a Micromechanical Calorimeter*, Appl. Phys. Lett. **69**, 40 (1996).

[41] S.L. Lai, J.Y. Guo, V. Petrova, G. Ramanath, and L.H. Allen, *Size-Dependent Melting Properties of Small Tin Particles: Nanocalorimetric Measurements*, Phys. Rev. Lett. **77**, 99 (1996).

[42] T. Ishitani, T. Ohnishi, and Y. Kawanami, *Micromachining and Device Transplantation Using Focused Ion Beam*, Jap. J. of Appl. Phys. **29**, 2283 (1990).

[43] R. Berger, Ch. Gerber, J.K. Gimzewski, E. Meyer, H.-J. Güntherodt, *Nanojoule Thermal Transfer in Micromechanical Heterostructures*, Micro-Electro-Mechanical Systems (MEMS), Symposium on Heat Transfer – Thermomechanical Sensors, DSC-Vol. 59, ASME 1996 p. 49, Atlanta, Georgia (November 1996).

[44] P.I. Oden, G.Y. Chen, R.A. Steele, R.J. Warmack, and T. Thundat, *Viscous Drag Measurements Utilizing Microfabricated Cantilevers*, Appl. Phys. Lett. **68**, 3814 (1996).

[45] R. Berger, Ch. Gerber, J.K. Gimzewski, *Nanometers, Picowatts, Femtojoules: Thermal Analysis and Optical Spectroscopy Using Micromechanics*, Analytical Methods & Instrumentation. Special Issue μTAS '96, 74 (1996).

[46] G.G. Stoney *The Tension of Metallic Films deposited by Electrolysis*, Proc. R. Soc. London Ser. A **82**, 172 (1909).

[47] H. Dugas, *Bioorganic Chemistry, A Chemical Approach to Enzyme Action*, (Springer, New York, 1996).

[48] R.G. Nuzzo, and D.L. Allara, *Adsorption of Bifunctional Organic Disulfides on Gold Surfaces*, J. Am. Chem. Soc. **105**, 4481 (1983).

[49] C.D. Bain, E.B. Troughton, Y.-T. Tao, J. Evall, G.M. Whitesides, and R.G. Nuzzo, *Formation of Monolayer Films by the Spontaneous Assembly of Organic Thiols from Solution onto Gold*, J. Am. Chem. Soc. **111**, 321 (1989).

[50] G.M. Whitesides, C.T. Seto, and J.P. Mathias, *Molecular Self-Assembly and Nanochemistry: A Chemical Strategy for the Synthesis of Nanostructures*, Science **254**, 1312 (1991).

[51] A. Kumar, H.A. Biebuyck, and G.M. Whitesides, *Patterning Self-Assembled Monolayers: Applications in Material Science*, Langmuir **10**, 1498 (1994).

[52] J.J. Hickman, D. Ofer, P.E. Laibinis, G.M. Whitesides, and M.S. Wrighton, *Molecular Self-Assembly of Two-Terminal, Voltammetric Microsensors with Internal Reference*, Science **252**, 688 (1991).

[53] K.D. Schierbaum, T. Weiss, E.U. Thoden van Velzen, J.F.J. Engbersen, D.N. Reinhoudt, and W. Göpel, *Molecular Recognition by Self-Assembled Monolayers of Cavitand Receptors*, Science **265**, 1413 (1994).

[54] R. Berger, E. Delamarche, H.P. Lang, Ch. Gerber, J.K. Gimzewski, E. Meyer, H.-J. Güntherodt, *Surface Stress in the Self-Assembly of Alkanethiols on Gold*, Science **276**, 2021 (1997).

[55] R. Berger, E. Delamarche, H.P. Lang, Ch. Gerber, J.K. Gimzewski, E. Meyer, H.-J. Güntherodt, *Surface Stress in the Self-Assembly of Alkanethiols on Gold Probed by a Force Microscope Technique*, Appl. Phys. A (Jan. 1998) in press.

[56] B.-H. Huisman, R.P.H. Kooyman, F.C. van Veggel, and D.N. Reinhoudt, *Molecular Recognition by Self-Assembled Monolayers Detected with Surface Plasmon Resonance*, Adv. Mater. **8**, 561 (1996).

[57] J. Brugger, G. Beljakovic, M. Despont, N.F. de Rooij, and P. Vettiger, *Silicon Micro/Nanomechanical Device Fabrication Based on Focused Ion Beam Surface Modification and KOH Etching*, Microelectronic Engineering **35**, 373 (1997).

[58] B.A. Cornell, V.L.B. Braach-Maksvytis, L.G. King, P.D.J. Osman, B. Raguse, L. Wieczorek, and R.J. Pace, *A Biosensor that uses Ion-Channel Switches*, Nature **387**, 580 (1997).

[59] R. Axel, *The Molecular Logic of Smell*, Scientific American, 130, October (1995).

[60] T.A. Dickinson, J. White, J.S. Kauer, and D.R. Walt, *A Chemical-detecting system based on a Cross-Reactive Optical Sensor Array*, Nature **382**, 697 (1996).

[61] J. Gardner, *An Introduction to Electronic Nose Technology*, (Neotronics Scientific, Warwick, 1996).

[62] J.W. Gardner, and P.N. Bartlett, *A Brief History of Electronic Noses*, Sensors and Actuators B, **18-19**, 211 (1994).

[63] Aromascan Inc., 14 Clinton Drive, Hollis, NH 03049; Sam, Daimler-Benz Aerospace, Richard Wagner Strasse 31, D-18119 Warnemünde.

[64] F.C. Tompkins, *Chemisorption of Gases on Metals*, (Academic London, 1978).

[65] K. Matsuura, Y. Ebara, and Y. Okahata, *Gas Phase Molecular Recognition on Nucleobase Monolayers Immobilized on a Highly Sensitive Quartz-Crystal Microbalance*, Langmuir **13**, 814 (1997).

[66] G. Harsanyi, *Polymer Films in Sensor Applications*, (Technomic, Lancaster, 1995).

[67] H.P. Lang, R. Berger, C. Andreoli, J. Brugger, M. Despont, P. Vettiger, Ch. Gerber, J.K. Gimzewski, J.P. Ramseyer, E. Meyer, *Sequential Position Readout from Arrays of Micromechanical Cantilever Sensors*, Appl. Phys. Lett. (Jan. 1998) in press.

[68] H.P. Lang, R. Berger, F. Battiston, J.P. Ramseyer, E. Meyer, C. Andreoli, J. Brugger, P. Vettiger, M. Despont, T. Mezzacasa, L. Scandella, H.-J. Güntherodt, Ch. Gerber, J.K. Gimzewski, *A Chemical Sensor Based on a Micromechanical Cantilever Array for the Identification of Gases and Vapors*, Appl. Phys. A (Jan. 1998) in press.

[69] Y. Su, A.G.R. Evans, and A. Brunnschweiler, *Micromachined Silicon Cantilever Paddles with Piezoresistive Readout for Flow Sensing*, J. Micromech. Microeng. **6**, 69 (1996).

[70] E. Delamarche, A. Bernard, H. Schmid, B. Michel, and H. Biebuyck, *Patterned Delivery of Immunoglobulins to Surfaces Using Microfluidic Networks*, Science **276**, 779 (1997).

[71] E. Delamarche, A. Bernard, H. Schmid, A. Bietsch, B. Michel, and H. Biebuyck, *Microfluidic Networks for Chemical Patterning of Substrates: Design and Application to Bioassays*, submitted to J. Am. Chem. Soc. (1997).

[72] R. Raiteri, and H.-J. Butt, *Measuring Electrochemical Induced Surface Stress with an Atomic Force Microscope*, J. Phys. Chem. **99**, 15728 (1995).

[73] S.J. O'Shea, M.E. Welland, T.A. Brunt, A.R. Ramadan, and T. Rayment, *Atomic Force Microscopy Stress Sensors for Studies in Liquids*, J. Vac. Sci. Technol. **B 14**, 1383 (1996).

[74] D. Rugar, C.S. Yannoni, and J.A. Sidles, *Mechanical Detection of Magnetic Resonance*, Nature **360**, 563 (1992).

[75] C. Rossel, P. Bauer, D. Zech, J. Hofer, M. Willemin, and H. Keller, *Active Microlevers as Miniature Torque Magnetometers*, J. Appl. Phys. **79**, 8166 (1996).