Sequential position readout from arrays of micromechanical cantilever sensors

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Sequential position readout from a microfabricated array of eight cantilever-type sensors (silicon technology) is demonstrated. In comparison with single sensors we find that mechanical disturbances from noise, such as from vibrations, turbulent gas flow, or abrupt pressure changes, can be effectively removed in array sensors by recording difference signals with respect to reference cantilevers. We demonstrate that chemically specific responses can be extracted in a noisy environment using a sensor to detect specific chemical interactions and an uncoated cantilever as reference. © *1998 American Institute of Physics.* [S0003-6951(98)00703-7]

In addition to their use for imaging and lithography, micromechanical devices have recently attracted much attention as sensor devices for: calorimetry,[1,2] photothermal spectroscopy,[3] surface stress detection,[4–6] and infrared detectors.[7–9] Seamless integration of such sensors in arrays provides an opportunity to increase the number and complexity of sensors and hence their selectivity to specific applications.[10–14] Our application of micromechanical cantilever arrays as sensors is focused on creating highly integrated multipurpose and selective (bio)chemical sensors for industrial, environmental, or portable applications (chemical ''nose''). This involves the use of differential measurements of mechanical responses from coated cantilevers for neural network data analysis. However, a principle problem exists in extracting small cantilever deflections in noisy environments such as those encountered in liquid and gaseous flow, and in the presence of external vibrations.

In this letter, we describe how we have overcome these limitations by using specific cantilevers in the sensor array as references. Our approach involves a novel method developed to read out the bending in sensor arrays in a sequential way using the beam deflection method (see Fig. 1).[15] Light from eight individual light sources[16] is coupled into an array of multimode fibers[17] and guided onto the sensor array (Fig. 2). Upon reflection, the light is collected by a position-sensitive detector (PSD),[18] and the photocurrents are converted into voltages. After amplification, the signals are digitized and stored. The eight light sources are switched on and off individually and sequentially detected by time-multiplexing as shown in Fig. 3(a).

By averaging signal responses, thermal or electronic noise originating from the amplifier can be reduced. However, noise acting on the array as a whole, when all sensors bend simultaneously, in response to noise sources from the environment (such as gas flow, abrupt pressure changes, and vibrations), are accumulated by averaging. To extract a true signal from this noise, the difference between the responses of a coated sensor cantilever and an uncoated reference cantilever was measured.

Sample sensor responses were determined from an array of four uncoated and four sensors coated with a 30-nm-thick electron-beam evaporated platinum layer on a 2-nm-thick titanium adherence layer. Operation of the sensor array in gas flow superimposes an overall deflection modulation to the sensors' responses as shown in Fig. 3(b). Note that the noise amplitude is approximately an order of magnitude larger than the true signal. A change of the deflection signal due to bending of the cantilever occurs upon hydrogen adsorption on platinum in the presence of oxygen.[1,19] It can be readily extracted from the data by calculating the difference between the responses of a coated sensor cantilever and those of an uncoated reference cantilever [Fig. 3(c)]. The signal-to-noise ratio can be improved by averaging sensor and reference cantilever responses, respectively. However, the difference between two coated or two uncoated sensors yields no net signal. The observed response of the platinum coated sensor provides a clear signal of the presence of hydrogen in the

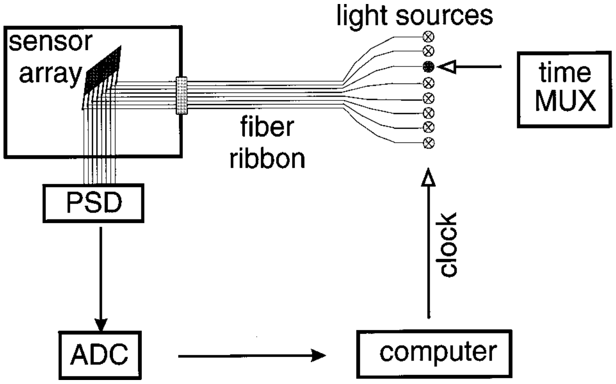

FIG. 1. Schematic setup of the chemical ''nose'' device illustrating the readout principle via optical beam deflection. Quasi-simultaneous readout of eight sensors is achieved by time-multiplexing (MUX) eight light sources which are guided by an optical fiber-ribbon onto the sensor array located in the analysis chamber. The reflected light from the sensors' surface is collected by a position-sensitive detector (PSD), then digitized by an analog-to-digital converter (ADC) and stored in a computer memory for further analysis. The computer also generates the clock pulse for time-multiplexing.

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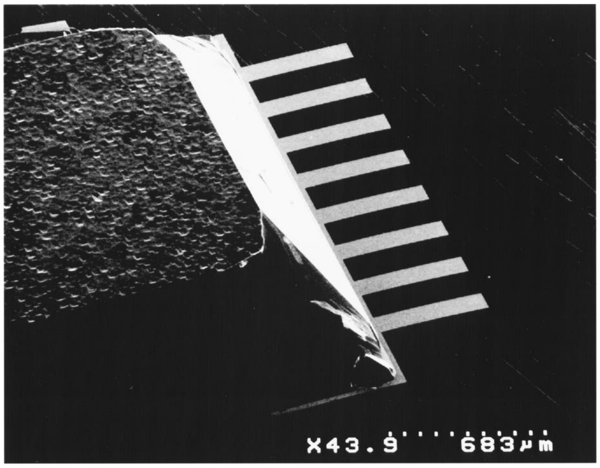

FIG. 2. Scanning electron micrograph of a microfabricated cantilever sensor array. Cantilever length: 500 μm, thickness: 0.8 μm, width: 100 μm. The distance between the cantilever edges is 150 μm, resulting in a pitch of 250 μm, which is a standard pitch in optical-fiber array applications. Typical spring constant: 0.02 N/m. Typical resonance frequency: 4 kHz.

noisy environment.[20] No such signature is observed when evaluating the response difference of platinum-coated and uncoated cantilevers when a different gas (e.g., carbon dioxide) is used, or when different receptor coatings (e.g., nickel) are exposed to hydrogen. Utilizing such characteristic signatures in neural network component analysis is the basis of developing a chemical ''nose'' for gases and vapors.

The readout procedure involves cheap, off-the-shelf components such as light-emitting diodes, fiber-optical ribbons, and standard detection electronics. The pitch of the fiber ribbon of 250 μm enables self-alignment of the light beams on the sensor array and facilitates operation. Currently, eight sensors are read out quasi-simultaneously, but there is no inherent principle limitation on the number of sensor elements. Unlike combined piezoresistive and piezoelectric detection schemes, no crosstalk due to common actuation and detection circuits is observed, as the reaction is transduced mechanically and the bending is read out optically.

Suitable commercial analog-to-digital conversion units for data acquisition can be operated at 100 kHz, resulting in a theoretical sampling rate of 12.5 kHz with eight sensors, which is further reduced by the time consumed by computer-controlled multiplexing and data acquisition. Practical limits are set by the switching of light sources (μs) and the response time of the PSD (20 μs). The beam deflection technique via a PSD is able to resolve cantilever deflections of fractions of nanometers.

In conclusion, we have demonstrated, for the first time, readout of mechanical deflection of elements in a cantilever array. This is achieved by a sequential optical beam deflection technique using an aligned optical fiber array. The advantages of employing reference sensors for differential measurements to compensate for disturbances have been shown. Additional advantages of the technique include elimination of calibration offsets such as refractive index changes originating from misalignment or from operation in liquids or gases. The method may in principle also be modified for imaging applications using micromechanical arrays such as atomic force microscopy when operating in noisy environments. Optical readout of mechanical signal transduction enables a minimization of crosstalk between cantilevers. Microfabrication optimized for mass production of such cantilever arrays can increase the number of sensors to at least 100 on an area of 5×5 mm^2.

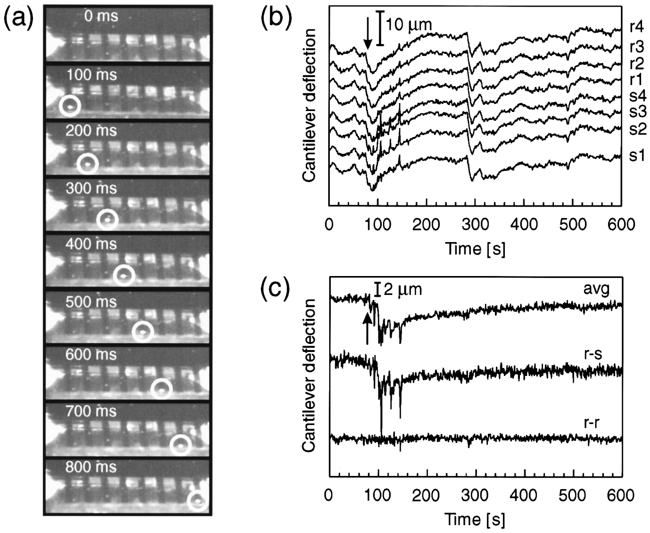

FIG. 3. (a) Optical micrograph of a micromechanical sensor array comprising eight sensors at a pitch of 250 μm appropriate for sequential and differential readout. The times indicated in the images label snapshot images of the array. Each individual sensor is illuminated sequentially for read out (marked by a white circle). (b) Quasi-simultaneous acquisition of the deflection responses of eight individual sensors in a noisy environment. Four sensors are uncoated (reference ''r1'' to ''r4'') and four sensors are coated by a 30-nm-thick layer of platinum (sensors ''s1'' to ''s4''). At first glance, all four curves look similar because the overall motion of the sensor array in the gas flow (nominal 1 mbarℓ/s) is dominant. (c) By evaluating the difference between a Pt-coated sensor and an uncoated reference cantilever, a characteristic signature of the reaction of hydrogen with platinum is found (''r-s''). By averaging the difference responses of four sensors and four reference cantilevers, the signal-to-noise ratio of this signature is improved (''avg'') resulting in a noise amplitude (peak to peak) lowered by a factor of ≈ 2 compared to the noise amplitude present by evaluating the difference in responses of a single sensor and a single reference cantilever. The difference between two reference (''r-r'') sensors yields no net signal. The arrow marks the time at which hydrogen was introduced into the reaction chamber.

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[20] Gradual static deflection change at a rate of ≈ 250 nm/s to a deflection value of ≈ 5 μm. The spikes indicate sudden deflection changes, similar to those observed in Ref. 1.